RIVERS AND ESTUARIES,

OR

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BY

W. HENRY WHEELER

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AN ELEMENTARY STUDY

BY

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WITH DIAGRAMS

LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
NEW YORK, BOMBAY, AND CALCUTTA
1913

PREFACE

THE Elementary Study which is contained in the ensuing pages, is to a large extent based upon Lectures on the subject of "Rivers and Estuaries," which were delivered in the beginning of 1911 at the desire of the Council of the Institution of Civil Engineers, and under the Vernon-Harcourt bequest, to the Students of the Institution in various parts of Great Britain; and upon further Lectures on the subject of "Streams and Tides," delivered in the University of Manchester to the Students in the Department of Engineering there, which is under the capable direction of Professor Petavel, F.R.S.

The object of the Lectures, which was kept in view during their delivery, was to furnish to these young Students information, and to offer to them counsel, which experience had taught the lecturer would have been of lifelong service to him had he heard and learned the same things in the remote period when he too was young.

To youth pertains the inheritance of the ages, but to youth also pertains a portentous faculty of forgetting; for which reasons amongst others, this Study is issued and is respectfully dedicated to the ENGINEERING STUDENTS of the present day.

W. H. HUNTER.

42, SPRING GARDENS,
MANCHESTER.
October, 1912.

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CHAPTER I

DIFFICULTIES OF THE SUBJECT

Amongst the multitude of matters which engage the attention and occupy the mind of the student of engineering, whether that student is still *in statu pupillari* or has reached more mature years, there are none more difficult, none in which there is greater liability to error, or in which the student is in greater peril of failing to take all material points into consideration, than those which relate to the subject of rivers and estuaries; the difficulties, as a matter of course, becoming particular when the study is directed to the case of a special river and estuary, and has for its objective the improvement of the waterway as a course for the free passage of floods from the land and of the tidal column from the sea, or for the purposes of navigation.

The reason for this is not far to seek. In dealing with questions relating to docks, canals, railways, and the like, men deal with works which are graven by art and man's device, are created by human minds and produced by human efforts, and which therefore can be controlled and maintained by the minds and efforts which brought them into being; while when attempt is made to deal in a practical way with matters which pertain to the flow of streams and the movements of tides, the attempt involves an effort, first to understand and then to guide and to regulate the great primeval forces to which such physical features as rivers and estuaries owe their existence, and by which they are in a sense maintained; although in the great majority of cases the conditions of their equilibrium are so unstable that endless change forms part of the actual economy of the maintenance.

The uncertainty and attendant vagueness which beset the subject may be illustrated (*a*) by propounding three questions of apparently puerile simplicity, and (*b*) by searching for suitable replies to these childish queries.

The questions are: (1) What is a river? (2) What is an estuary? (3) Where does the one end and the other begin?

Beginning with the first question. It will be found that etymology can offer but little assistance to the student in his quest. Our word "river" came to us from the Latin *ripa*, a bank; a derivative of which is *riparius*, a bank by which water is confined (from which again came the familiar word "riparian," an adjective which is frequently used with more hardihood than discrimination, in order to denote what are alleged to be "riparian rights" of "riparian proprietors" by owners of property whose land does not at any point touch the bank of the stream or watercourse, in respect of which the rights of a bank owner are claimed), but which has no direct connection with the water which flows by or surges against that bank; and it can hardly be deemed that a definition of a river which excludes the fluid therein will satisfy an engineering student: while if it be contended that a river is a body of water confined between *riparia* then the Mediterranean Sea is a river! If etymology be abandoned as hopeless and the precise phraseology of the jurist be prayed in aid, so far as English law is concerned the result will be disappointing, as if the Salmon Fishery Acts (1861 to 1866) be taken as an illustrative example it will be found that the word "river" is defined as including "such portion of any stream or lake with its tributaries, and such portion of any estuary, sea, or sea coast" as may be declared by the Secretary of State to belong to any particular river.[1] The phraseology of American law seems at first sight to be more satisfactory, "As a general proposition wherever there is a steady uniform current of water it constitutes a river,"[2] but reflection will show that though there is a "steady uniform current" through the Lake of Geneva on the one hand, and through many a tiny watercourse over which a boy can hop or a cat jump on the other hand, yet neither of the phenomena would be described by an engineer as a river.

The efforts of science have not been much more successful. "The term *river*," said the late Professor Robison, "is appropriated to a considerable collection of waters, formed by the conflux of two or more *brooks*, which deliver into its channel the united streams of several *rivulets*, which have collected the supplies of several *rills*, trickling down from numberless *springs*, and the

[1] "The Law of Waters," by H. J. W. Coulson and U. A. Forbes, p. 385.
[2] "American Law of Easements," by Emory Washburn.

torrents which carry off from the sloping grounds the surplus of every shower:" a definition which seems to be at once reminiscent of the nursery rhymes of early youth, and of the well established principle in English law that if the drains from "two or more" inhabited houses discharge into a "brook," that brook becomes a sewer, and passes under the control of the local Sanitary Authority.

The only answer to the question which presents itself is that a river is the main course by which the run-off from a watershed is borne to the sea, a definition which is open to the criticism that tried by the letter of the proposition the Missouri is not a river, the only possible reply to the criticism being that it is obvious that the matter is one of degree.

The second question is, if anything, more difficult than the first, as the minds of most people are in a more nebulous condition about the estuary than about the river. The derivation is again from the Latin: this time from the verb *æstuo*, to boil or to foam. So that in strict speech the estuarial line is that on which the incoming tide meets and foams against the fluvial stream of land water struggling to make its way into the sea, to which "all the rivers run." The estuarial line changes its position from moment to moment during the period of flood, and changes its total stroke from tide to tide, so that the only practical definition of an estuary is, that it is an area on the sea coast, an indent into the land, in which estuarial lines are formed at certain times and under certain conditions; a definition about as precise as that offered by the bewildered statesman in the old story, from whom information was demanded as to the actual duties of an archdeacon, and who replied that, so far as he understood the matter, an archdeacon was an ecclesiastic "who from time to time performed archidiaconal functions."

If such difficulty be found in formulating a description of either river or estuary in terms which will stand the test of criticism, it may be that at this point the student will be prepared to avow himself of one mind with the distinguished law lord, who possesses as astute a mind and as acute an intellect as any man of his generation, and who on one occasion, first stated frankly that he never could make out where the estuary ended and the river began, and then tore to tatters every solution of the problem which was presented to him.

This is by no means a mere matter of words, or of quibbling

about words. Cases might be cited in which engineering witnesses have floundered, and learned judges have gone wrong because they were not clear in their own minds as to what the word "river" really means; while the point at which the estuary ends and the river begins must be authoritatively determined somehow; as in an estuary, the right-hand bank is on the starboard side of a vessel which proceeds inland from the sea; while, in a river, the right-hand bank is, on the contrary, on the right of an observer who stands looking in the direction in which the stream is flowing; and any engineer who has been accustomed to the deposit of plans for private Bills in Parliament, knows how many mistakes are made in this respect in the "bank sections" which are required to form part of the deposit, when a river and an estuary come within its scope.

The suggestion to the student is that the point of division between the river and the estuary should be determined by the line which marks the limit of the flow of the highest tide when uninfluenced by the wind, except perhaps in such cases as those in which the dividing line has been or is to be arbitrarily fixed by artificial works.

CHAPTER II

PHYSICAL DIFFICULTIES

We now turn from difficulties of term and description to difficulties of a physical sort; difficulties which have the quality of inherence because they are native to the operation of the forces to which the earth owes her form and value, and the streams and the tides owe their existence.

The area of this planet, measured as an oblate spheroid at the mean level of the sea, is about 192,000,000 square miles, of which some 55,000,000 miles are land, and 137,000,000 are sea.

Excluding past periods of geological age, which are not within the ambit of this study, the proportion between land and sea in historic times seems to have been fairly constant: which implies that the effects of the two great antagonistic forces of Nature have, taken as a whole, balanced each other.

These two forces are gravitation, which leads to concentration of material, and radiation (that is to say, dissipation of energy in the form of heat), which tends to contraction. The one force, aided by minor and subsidiary forces, leads to the lowering of the level of the land and the deposit of the material thus won from the land, in the bed of the sea. The other force causes irregular contraction in the crust of the earth and produces as a consequence of the contraction, serration, upheaval, lifting of the crust or of parts thereof against gravity. This action, which shows itself in what geologists describe as "folding, crushing, and overthrust faulting," is the genesis of many of the mountain ranges, and is also the cause of such processes as those of which the signs were noted by Dr. Darwin on the coast of Chili in 1835, when measurements which he made led him to conclude that in comparatively recent times, a long strip of that coast has been upheaved by successive movements, to heights of from 400 feet to 1100 feet above the level of the sea.

The effect of such a movement upon the estuarial indents of that coast and upon the rivers which drain into them can readily be imagined, but it is in the *local* operation of the forces of gravity and of radiation that the student who is concerned in the maintenance and improvement of rivers and estuaries is interested, rather than in such remarkable phenomena as those described by Dr. Darwin.

Gravity is of itself a static and conservative force; but acting in conjunction with Nature's carving tools, air, water, chemical effect, extreme heat, severe cold, and such-like; the combined effect of the whole, working as they do "without haste and without rest," is change and transformation. Solid rocks are broken up into ever diminishing fragments, parts are converted into particles, masses are reduced to boulders, boulders to pebbles, pebbles to sand, and sand to imponderable silt; while parts and particles thus formed are seized by the flowing waters, and are hurled, swept, rolled, or borne onwards and downwards until a new resting-place is found for them as parts of low-lying and fruitful lands, as encumbering banks in the bed of an estuary, or as ever-increasing deposits in the marginal depths of the sea.

The sum of the whole matter may be expressed in two words, DISINTEGRATION and TRANSPORTATION. The disintegrating effects of the agencies described, subject refractory masses to the operation of gravity, through which operation again water falls upon the earth in the form of snow or rain, and under which it seeks a plane of equilibrium at the sea level from whence it originally proceeded, so that the great cycle may be completed; but the point here is that the water does not return empty handed to the source from whence it came, but bears with it, on its way, the *débris* of the mountains and of the hills.

At this point it is necessary to revert to the definition of a river already suggested, as such will serve for the present purpose; that is to say, that a river is the main course through which the run-off from the watershed is borne to the sea; or, in other words, is the line of least resistance to the discharge of the rainfall, as it is obvious that this line of least resistance is the line upon which the *débris* from the earth will be transported until some more or less stable resting-place is found for it.

The earth never becomes outworn, because its face is ever being renewed. The process of renewal is one of disintegration and of transportation; and beneficial as the process is when looked at

from one point of view, from another point of view it is big with peril of injury to the river and of destruction to the estuary. Failure to appreciate this fact, and consequent inability to apprehend the potency of the forces which operate to the prejudice of watercourses, have led to the irreparable injury of more than one river and to the virtual ruin of more than one estuary, through futile efforts for improvement and reclamation by means of works which were unadapted to the conditions; the fact being that the conditions were not understood.

The locality where the river with its load of *débris* debouches upon the coastline demands the special attention of the student, as in many cases it is at that place that the conditions are complicated by another phase of the operation of gravity. The phase is that known as tidal action, an action which progresses in two stages primary and secondary. The primary stage has its most marked effect in the marine belt which girds the southern portion of the globe, the effect of the secondary stage can be observed on the greater part of the coastlines on the earth.

The primary stage is due to the direct attraction of the sun and of the moon, which cause heaping-up of the mobile waters in the ocean, sometimes at one and the same degree of longitude, when the lines of attraction of sun and moon are co-incident, at other times at degrees widely apart from each other, when the lines of attraction are diverse in direction.

In the secondary stage gravity acts as a levelling and, therefore, as a distributing force, through which the effect of the heaping up in the Southern Ocean is spread over nearly all the water areas connected with that ocean, causing rise and fall in these areas generally speaking twice in each day, or in other words producing the diurnal tides.

The heaping up in the great southern belt is of itself but small in height, not more than two feet at most,[1] when the attraction of sun and moon are co-incident, at which time the spring tide period follows the heaping up. It would be impossible, and is unnecessary, to deal in an elementary study with this primary stage of the operation of gravity, or with the intricacies of the distribution of the wave, or with the almost infinite diversity of

[1] Sir George Airey calculated that the greatest tidal height in the Southern Ocean is 1·95 feet, of which 1·34 feet are due to the attraction of the moon, and 0·61 foot is due to that of the sun. Such observations as have been taken, and such measurements as have been made, have confirmed the calculation. "Tidal Rivers," by W. H. Wheeler (Longmans, Green & Co.), p. 82.

form and circumstance which in some parts of the earth greatly magnify the tidal oscillation, as in the Bay of Fundy, the deep bight between New Brunswick and Nova Scotia, where the tidal range is about fifty feet at springs; or obliterate it altogether as in the Mediterranean, or produce regularly a range at spring tides of nineteen feet in the Bay of Panama in the Pacific Ocean, while in Limon Bay in the Atlantic, only forty-nine miles away, there is but a fitful and irregular tide, which seldom exceeds two feet in height, and frequently disappears altogether.

The effect of the tidal rise and fall at and upon the mouth of any river is enormously influenced and complicated by wave action, the occasion of which is the ceaseless variation of barometric pressure on the surface of land and sea. This variation is but another phase of the operation of gravity, but it leads to vast atmospheric disturbances, now causing hurricanes and tornadoes which lash the waters into fury, and again producing soft breezes and gentle zephyrs which cajole them into languid movement, the difference being mainly one of degree. Where there is movement of marine waters first in the form of "waves of oscillation" in the greater depths, subsequently in that of "waves of translation" when the depths begin to diminish, and finally in that of "rollers" or "breakers" on the shore: there is always movement of material, which is in fact an effort on the part of the sea to cast up again on the land the terrigenous material with which its bed is blanketed for a width of about three hundred miles from every coastline which abuts upon an ocean or a great sea. This belt of terrigenous deposit extends to an ocean depth of about four miles and has at times been termed the "transitional" or "critical" area. The importance of the belt may be measured by two facts, (1) that it covers one-fourth of the earth's surface (or in other words that the "critical" area is equal in extent to two-thirds of the combined areas of all the lands on the globe), and (2) that in it tides and currents produce their maximum effect in the transport of material, this effect having been traced in some instances to a depth of three hundred fathoms.[1]

[1] These facts were determined by the celebrated *Challenger* expedition of 1872–6, through which also the existence of "Cosmic dust" (which after the manner of fine rain falls upon the ocean floor, and accumulates thereon) was detected. H.M.S. *Challenger* was commanded by Captain G. S. Nares, R.N. (now Sir George S. Nares, K.C.B., F.R.S.), and the expedition was at the outset led in a scientific way by the late Sir Wyville Thomson.

The combined effects of tidal and wave action are varied but are sufficiently apparent in most places. There are few parts of the east coast of England where cliff destruction may not be studied; many parts, such as the Norfolk coast, where that destruction is proceeding on a disastrous scale, while collateral mischief in the production of shoals and quicksands, such as those which encumber the mouth of the Thames, is also proceeding. On the other hand, practically the whole of the eastern coast of North America, from Long Island in the north to the Bahama Islands in the south, has been built up into fertile territory by material first derived from the land, then deposited in the sea, and finally disturbed by wave action and transported along the foreshore by the combined influence of the winds, littoral currents, and tidal streams, until the *débris* has found resting-places on the foreshore above the level of the tidal range. Wherever this operation is in progress it is obvious that the creeks, estuaries, and rivers by which the coastline is interrupted and indented are in some cases in danger of injury, in others in peril of destruction. It is true that the process results in permanent advantage to the foreshore, but it is equally true that it frequently results in detriment to the creek, estuary, or river into which the unwelcome material has been flung by the restless waters, so that works for the maintenance and improvement of features of such material importance as the indents in question, have usually for their objective the remedying of injury caused by the deposit of materials within their banks and the prevention, as far as such is possible, of further injury by further deposit.

But this combined action of wind, wave, and tide, upon materials which have been deposited in creeks and embayments in coastlines is not always detrimental to the depths in or the capacities of such indents.

On the shores of Bass' Strait which, in the Commonwealth of Australia, divides the southern coast of Victoria from the northern coast of Tasmania, there are several bays, of which Anderson's Bay may be taken as an example; into which the waters of many rivers flow, bearing with them *débris* from the lands in the manner already described. The *débris* is deposited within the shores of the bay, it is hardly necessary to add that no attempt to remove the material by artificial means has been or is ever made; yet so far as the available information goes, no shoaling of a material sort can be detected in the indents; in the majority of the

cases the capacity below high-water mark seems to have suffered no diminution.

The explanation of the apparent paradox is that under certain conditions of exposure and of weather, materials derived from the land which have been deposited in the embayments, are stirred up again by wave action, and under the influence of the tides and of strong and steady winds are hurled back by the sea upon the shore, sometimes far above high water of the highest tides. The materials thus hurled back by the sea, together with the shells and other marine accessories which have been borne along with it, are seized by the winds, are built into sand dunes and hills, and are again slowly but surely borne inland in the track of the prevailing winds, until large districts are overspread thereby; in some cases to the advantage of the affected districts, in others with reverse effect; but always to the advantage of the bays which are thus relieved from the incubus of the terrigenous deposit.

CHAPTER III

THE PURSUIT OF INFORMATION

THE assumption may now be made that a student who has taught himself to appreciate the difficulties with which he will be confronted, has been called to deal professionally with some particular river or estuary with a view to the design of works and the conduct of operations for the improvement and development thereof; and the question will be what course is that student to take.

The first essential, the fundamental requirement, is that he should collect for himself information as to the *régime* of the stream and the movements of material, (1) in its course and (2) at and about its mouth. It will be found that the task is by no means light or easily accomplished. The facts are frequently wrapped in obscurity, the forces are mutable both in direction and duration, and are incapable of accurate determination. Gradual changes both in form and in meteorological conditions are taking place in most watersheds, and the materials for the history of these changes are usually meagre to the point of attenuation.

The *régime* (or *regimen*) of a river is a term which has sometimes afforded sport for dignitaries such as His Majesty's Judges, Chairmen of Select Committees of Parliament, and other great personages. Occasionally the interest in the sport has become intense when some unhappy witness who has used the word as terse and convenient, has found himself unable to define it exactly when authoritatively required to do so.

The *régime* of a river may be described as the integration of all the forces which maintain the river in the form in which it exists. Changes in the river are of themselves evidence of changes in the *régime*, from which it follows that though the *régime* is an order to be studied, it is not a fetish to be worshipped as though it were incapable of improvement.

It will be found that the information to be acquired, and tabulated, as to the *regimen* of any river, is as varied as it is voluminous.

The late Mr. David Stevenson divided rivers in a general way into three parts,[1] viz.

(1) The river proper.

(2) The tidal compartment (*i.e.* the estuary).

(3) The sea proper.

The division is not altogether exact, but Mr. Stevenson quoted judicial authority for it, and it suggests a system of classification of the data which are to be obtained and of the features which are to be observed.

For the river proper, in the first instance the area of the watershed should be ascertained and the general character of the surface and of the nature of the sub-soil noted, the rainfall should be measured and the maximum and the minimum quantities which are discharged in flood times and in dry seasons respectively, should be estimated as nearly as is practicable. In many cases but little time or opportunity can be found for rain gauge and other similar measurements and observations, as the matter in hand must be brought to a conclusion of some sort too rapidly to admit of protracted observation: in these cases such information as has been obtained should be compared with the corresponding figures in any known watershed in which the conditions are similar or nearly similar to those in the area under investigation, and a factor of comparison evolved which, applied to the tabulated results in the watershed in which accurate information as to rainfall and run-off is available, will furnish particulars which are not likely seriously to mislead the observer who is working in the new ground.

When this assistance fails, help in estimating the quantities of maximum run-off may be obtained by observing and levelling flood marks which can almost always be discovered, while for minimum discharge when all other methods fail it is usual in this country to assume an average run-off of 0·25 cubic foot per second from an area of a 1000 statute acres; a constant which is largely used by waterworks engineers in preliminary inquiries relative to the run-off which may be expected from comparatively unknown catchment areas, but which, if employed for the purpose suggested here, should be accepted subject to the qualification that even in

[1] "Canal and River Engineering," p. 67.

a case in which the constant may be approximately correct for the whole of the watershed of the river, it will vary considerably in different parts of the watershed, being below the average in the higher altitudes and perhaps much above it in the lower levels. Recent gaugings of an accurate sort have shown this conclusively.

The angle of inclination of the trees will show the direction of the prevailing winds, while information will always be forthcoming from the inhabitants of the district as to the severity and duration of winter frosts, depth of snow, etc., as these are circumstances which impress themselves upon the memories of even the least intelligent of natives; but this information should be received with caution, as the dramatic instinct which is innate in humanity often leads a narrator, in an amiable desire to make his story interesting, to sacrifice accuracy to picturesque detail.

Then, as the course of the river is followed downward, attention should be paid to the bends in the more tortuous parts, the facts that concavity is evidently increasing here and that shoaling is taking place there should be noted; and particularly places where Nature has pushed concavity so far as to indicate efforts for the improvement of the watercourse by forcing it in a new direction should be marked, for at these points the efforts of Nature may be effectively aided by engineering knowledge and skill.

Cross-sections of the river are indispensable. It is essential that the sections should extend sufficiently far on each side of the stream to cover the range of the highest flood, and that the sections should be spaced so as to show the transverse form of the river at each bend. Subject to this provision it will be found in most cases to be sufficient for the purposes of a preliminary survey if the sections be taken at distances of about one mile apart.

On the line of each section a gauge must be fixed so that the ever-varying levels of water at each point may be read and recorded when the section is taken, and from time to time afterwards. The whole series of gauges should be referred to one horizontal datum, so that the inclinations of the surface of the stream may be determined from the levels read on the gauges. The inclinations are commonly described as the "hydraulic gradients" of the river, and upon them the velocities of the flow of the stream depend in large measure.

Actual observations of the velocities of the flow, taken at convenient parts of the stream, ought not to be omitted in the investigation, as in conjunction with the areas of the cross-sections

they render it possible to calculate the volume of water discharged by the river with accuracy at different stages. Velocity of flow is observed in various ways. Sometimes current meters, fitted with a small screw or propeller, from which worm gear is driven which records the travel of the stream in a given time, are used. These meters are not suitable for use in silt-bearing streams, as the friction due to the interposition of even a grain or two of silt between the plates of the meter in use has a very sensible effect upon the revolutions of the instrument, and consequently upon the speed recorded thereby in any given time. Of late the "Pitot" tube in which velocity is converted into energy expended in raising a column of water against gravity, and the result measured in a graduated scale, has been successfully employed. For ordinary open streams no method of measurement of velocity is superior to that in which rods of equal diameter throughout, weighted so as to float at a depth as nearly as practicable equal to the actual depth of the part of the stream in which they are to travel, are used; the times at which the rods pass into and out of an accurately measured length of the stream (which should not be too long) being carefully determined by observers, one of whom should be equipped with a stop watch. This was the method employed by Messrs. Humphreys and Abbot in their classical investigation of the *régime* of the Mississippi river.

Still proceeding downwards a zone will be reached in which the first evidence of tidal action (observed through the checking of the fluvial stream which becomes apparent there) will be noted; the significance of the evidence being that the head of the tidal compartment, of the estuary of the river, has been discovered, and that somewhere thereabouts the line which is to be fixed as the boundary between the river and the estuary will be found.

Below this line the gauges to be fixed will be tidal gauges, by means of which the "Establishment of the Port," that is to say, the normal rise and fall of the tides, the times and heights of high and low water at springs and at neaps, the relationship between the tides and the lunar phases, and the manner in which the tides are affected by the direction and strength of the winds, is to be determined, first tentatively, and after more extended observations, with as near an approach to finality as possible.

For this purpose self-registering tide gauges such as are now

made by Sir W. H. Bailey and Co. and other well-known firms of British Engineers offer overwhelming advantages. They are worked by the tides themselves, their results are much more reliable than those obtained from human observers, their records are continuous, and if they receive proper attention they never stop.

Two circumstances militate against the use of these gauges in preliminary surveys, (1) their cost is considerable, and (2) it is difficult to find sites for them at which the whole range of the tide may be measured without thrusting the gauges too far out into the estuary.

When tide gauges in the form of graded boards are used, this difficulty is got over by stepping the boards on the shelving foreshore in such manner that as the tide rises and the observer is driven inshore, he is able to continue his reading on one board after another until he reaches the line of high water.

No problem in the whole series of proceedings requires for its solution the exercise of greater care and judgment than that of the selection of the sites for the tidal gauges. Estuarial tides are so fitful and wayward, so given to form eddies here and backwaters there, that experience has shown that it is possible to obtain results from a series of observations of which each item is accurate in itself, but which taken as a whole are absolutely inaccurate and altogether misleading.

The gauges throughout, whether in the river proper or in the tidal compartment, should be set at the same datum line, plus and minus readings should be avoided for the sake of simplicity and for the avoidance of error, from which it follows that the datum line should be established at a level sufficiently low to permit of all the observations being read upwards from zero, even on the most seaward of the series of gauges. In this country a datum line at a level of fifty feet below Ordnance Datum (which represents the mean level of the sea at Liverpool) will usually fulfil all the conditions required.

The physical conditions in the tidal compartment must be observed with even greater exactitude and if possible over a more prolonged period than those in the river proper, as it is not only that the tides in an estuary are fitful but that the ways of the estuary itself are as whimsical and perverse, as apparently insubject to law and regardless of order, as if the indent were seeking for a share in its own administration.

Notwithstanding these difficulties the dictum laid down over sixty years ago by the late Captain E. K. Calver, R.N. (who was an authority on the subject) in his work on "The Conservation and Improvement of Tidal Rivers" which was published in 1853, that "Nature will answer faithfully if we interrogate her—not if we interrogate ourselves," has been proved by the experience of many men in many lands: while it was an aphorism of the late Sir Benjamin Baker that "Nature never deceives you if you watch her long enough." There is no other way for those who would follow Nature's intricacies in an estuary, but to "watch her long enough."

Positions of rocky reefs and of hard shelves are to be carefully noted and shown on the plan, as these will generally be found to form nodal points on which the low water channels in the shifting sands swing as they writhe to and fro. All possible information should be obtained and all indications should be observed of the manner and extent of this movement of the unstable channels in the estuarial area. The influences which effect the movement are of vital importance and should be carefully studied. The tidal flow and ebb, the floods from the land, the varying winds all combine to produce changes more or less gradual but mercilessly continuous and sometimes destructive, while at time changes (to which further reference will be made hereinafter) which may almost be described as violent take place in the most unexpected manner and from apparently incommensurate causes.

Attention should also be paid to the cliffs or banks by which the tidal compartment is bounded, as if these are formed of friable materials, as is usually the case, constant waste will add sensibly to the masses of sand and silt which encumber the bed of the estuary and will proportionately add to the difficulties attendant upon any attempt to regulate and improve the channels.

In many cases the encumbering masses are swollen and the difficulties are enhanced by the barbarous and filthy practice which still obtains, of pouring crude sewage into tidal waters. Unchecked by law, unhindered by public opinion, and unabated by municipal effort, the pollution continues day and night through all seasons and in all times, even in cities and amongst people to whom it would be a deep affront if any question were raised as to their status, or as to their claim to a place in an organized civilization.

In respect of the movements of sand, silt, and sludge into, in,

and out of the estuary, and of the effect upon such movements of any projected works, questions of great importance, upon which much must depend, will arise as to the existence or otherwise of periods of slack water at or about high tide at different points during flood. Reliable answers to these questions cannot be obtained from the records derived from the tidal gauges. Nothing but direct observations at regular periods made from a boat moored in the tidal stream and by means of weighted rods and log-lines will meet the case. Observations of this sort have shown again and again that at places where deductions drawn from co-tidal curves, laid down from readings from misplaced gauges, have led to the conclusion that lengthened periods of slack water and of consequent deposit, would be found to exist; the change from flood to ebb took place with such rapidity that the change actually occurred within the very brief period covered by one observation, that is to say that a float sent forth to measure the flood velocity came back upon the observer under the influence of the first of the ebb currents.

CHAPTER IV

FLOW ROUND BENDS

WHILE considering the questions relating to the bends of the river, the student may be advised to take into account, as being worthy of very careful consideration, principles which were enunciated by Prof. James Thomson, F.R.S. (a brother of the late Lord Kelvin), nearly forty years ago, to which little attention has been paid by the majority of engineers, and which seem to have been ignored by scientists. Prof. Thomson first stated as a matter of hydro-kinetic law, and then showed experimentally, that contrary to the opinion generally held, a stream flowing from a straight into a curved channel flows along the bend with a greater velocity on the inner or convex, than on the outer or concave bank, something after the manner of a "whirlpool of free mobility." Yet erosion takes place in the concave bank where the velocity is least, and deposit occurs on the convex side where the velocity is greatest.

His explanation of the apparent anomaly was, that on any cross stream line of particles in a curved channel, water pressure under the influence of centrifugal force increases from the inner bank to the outer, thus causing a transverse inclination on the surface of the stream, the angle of inclination being upward from the inner to the outer bank.

But concurrently the lower laminæ of water in motion will be retarded by frictional resistance, and will therefore be less influenced by centrifugal force than the laminæ above; hence the lower laminæ under the stress of the greater hydraulic pressure on the outer bank will flow diagonally across the channel toward the inner bank, and will expend the remainder of the energy stored in them, in partially rising up that inner bank, and thus forming a sort of cushion between the bank and the stream lines. This cushion will protect the bank from erosion, while the material borne or

rolled along by the laminæ of water in diagonal motion will (or *may*, as Dr. Thomson put it) find a place of deposit there. On the other hand, the surface water on the outer bank will under the influence of gravity descend along that bank, eroding its face in their descent, and providing material for transport by the lower laminæ in their diagonal progress across the channel.

The different lines of motion of the laminæ of water are illustrated in the annexed diagrams, of which Fig. 1 represents

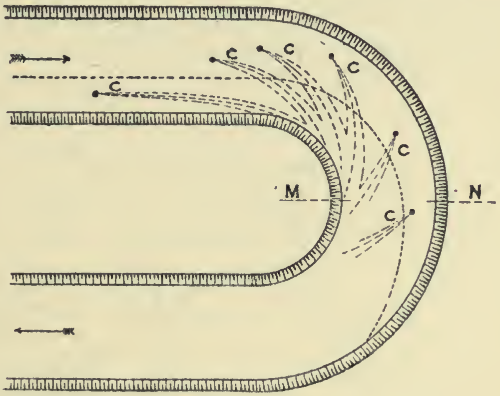
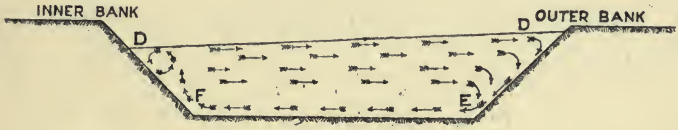


FIG. 1.

a view in plan of part of the experimental tank in which Prof. Thomson, by means of threads, of particles of aniline colours, and of seeds, showed the lines of flow (marked CCCC), while Fig. 2



SECTION AT M–N.

FIG. 2.

represents a cross section of the channel in the tank in which DD shows the surface of the water as raised by centrifugal force at the outer bank, while DE and DF respectively represent the descending laminæ on the outer bank, and the ascending laminæ on the inner bank. The eddy action in the ascending laminæ near the surface of the water could be clearly seen in the experimental tank.

A further protection to the inner bank is occasioned by the tendency (which could also be readily observed) of the upper laminæ in the stream to flow in lines of greater radius than the line of the curve of the inner bank, leaving space between the inner bank and the line of flow. This space will be occupied by water which has been moving along the bottom of the river, which consequently is flowing at greatly reduced velocity, and which therefore causes deposit of material which has been transported by the stream from higher parts of its course.

The movements of the different lines of water which help to make up the flow of the stream will be followed more readily if Fig. 3 be examined. In Fig. 3, which is derived from Prof. Thomson's diagram, the line AB represents a vertical film of water moving along and parallel to the straight bank of the river. At B the commencement of the curve is reached, and under the influence of well-known law the film diverges from the inner bank of the curved channel and flows along the line BC. The space between the inner bank and BC is left for occupation by water which has moved down stream along the bottom of the channel on some such line as that shown by DBE, and which bears in suspension silt derived from a higher part of the course of the river.

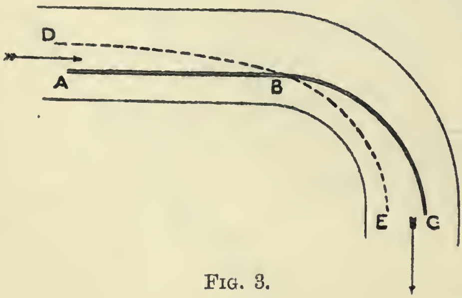


Fig. 3.

It will appear from the foregoing that Dr. Thomson held that growth on the convex side of a river bend is due to material derived from two sources, (1) from the neighbouring concave bank of the stream, and (2) from banks and bends in "higher parts" of the river course.

Some difference of opinion has arisen as to what the learned Professor's view on this point really was; but it seems to be fairly clear that the conclusion thus stated was that at which he arrived, although he asserted it in somewhat hesitating and tentative terms, to the effect that "ordinarily or very frequently" in rivers in alluvial plains it will be found that detritus travels down stream along the bottom seeking for resting places, and

that in such plains deposit is on the average greater than erosion, except when "geological changes" have occurred by which the causes which produced the alluvial plains in question have been rendered extinct.

The student who may have any doubt on the point may find a solution for himself first, by spending a day on the banks of a river in flood and secondly, by noting the rapidity with which a bend, such as that shown in Fig. 4, becomes filled up by material derived from "higher parts" of the river, when the bend is cut off either artificially or by natural effect in the manner shown by the hatched lines. There need be no doubt about the matter; erosion and transport of detritus by water are functions of velocity, and

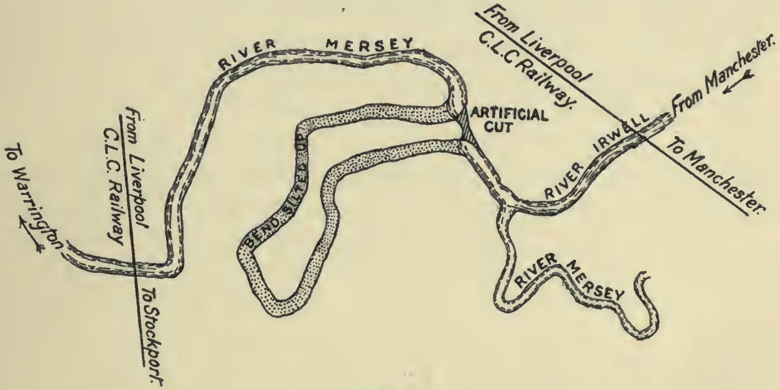


FIG. 4.

when velocity is violently increased by flood action in a river, both must take place, until the eroding and transporting powers of the greatly increased volume of water passing over and through the river's bed and banks are exhausted.

One reason why Prof. James Thomson's valuable contribution to engineering knowledge in respect of the flow of water round curves has never received the attention which it ought to have commanded, is that the results of his interesting study were published in an ineffective manner. These results were never collected by him or by any one else, and even yet are only to be found in what may, with the deepest respect, be described as the catacombs of modern days; that is to say, in the transactions of Corporations so learned that the ordinary man, who is always willing to "let the dead past bury its dead," will never venture

to attempt excavation amongst the relics, except under the stress of peculiar and personal interest.[1]

Notwithstanding the fact that the manner of the publication of Dr. Thomson's results was not such as to assist inquiry, some responsibility does lie upon scientists and upon engineers (not to say, students) who undertake to deal with questions relating to the flow of water, to make themselves acquainted with them.

The following quotations from well-known standard works—one a charmingly told geological record of the development of the earth, entitled, "The Story of our Planet,"[2] and the other an engineering memoir of a great and successful American effort for the improvement of the Mississippi River, may serve to add point to this suggestion. In the first of these standard works, the author, whose *status* in the world of science may be gauged by the fact that he is a Past-President of the British Association, says, "Suppose, for instance, the course of a stream represented by the lines PAR, QBS, in the annexed diagram (Fig. 5), to change at the points AB, from a straight line to a curve, the line of quickest motion which is parallel to AP, BQ will pass through C, the middle point of AB. This line below C will not curve in correspondence with the banks so as to divide the space between

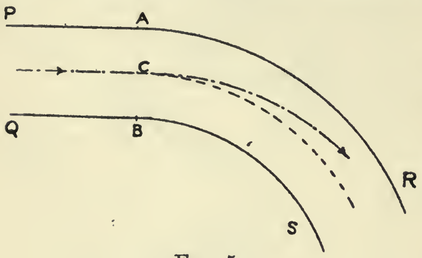


Fig. 5.

[1] Short papers by Prof. James Thomson were included in the *Proceedings of the Royal Society*, vols. xxv. (p. 5) and xxvi. (p. 356), and in the *Proceedings of the Institution of Mechanical Engineers* for 1879 (p. 456). A brief paragraph referring to his conclusions (erroneously attributed to his better-known brother, Lord Kelvin) was published in 1908 by Mr. F. C. Lea, in his work on *Hydraulics* (p. 520). The conclusions were also referred to by Prof. Unwin, F.R.S., in his comprehensive article on "Hydraulics," in the eleventh edition of the *Encyclopædia Britannica*, vol. xiv. (p. 72). With these exceptions Prof. Thomson's work seems to have been overlooked until quite recently when, on the completion of the Collected Edition of Lord Kelvin's scientific work, "the idea impressed itself on others that there should be available a full record of the work" of Prof. James Thomson also. As a result of that happy idea the *Collected Papers in Physics and Engineering*, by Dr. Thomson, selected and arranged by Sir Joseph Larmor (the Secretary of the Royal Society), and Mr. James Thomson, M.A., have just been published in a single volume by the Cambridge University Press, and have been thus brought within the convenient reach of every engineering student.

[2] By Prof. T. G. Bonney, F.R.S. (p. 124).

them equally; but it will be nearer to the outer bank than the inner bank, because, in conformity with the well-known law in dynamics, "a body in motion will continue in motion uniformly and in a straight line until acted upon by some external force." So the line of quickest motion would continue to be a straight one were it not for the resistance of the outer bank, and the curve which it actually does follow lies rather on that side of the channel. Thus beneath this bank *the water flows more swiftly*, and its erosive effect is greater than on the opposite side."

In the second work referred to, of which the title is "A History of the Jetties at the Mouth of the Mississippi River,"[1] the author quotes a long, carefully drawn letter (dated March 15, 1874), addressed to the Hon. William Windon, United States Senate, Chairman of Committee on Transportation Routes to the Seaboard; in which the late Mr. James B. Eads, a distinguished American engineer, stated his views of river hydraulics as follows: "The popular theory advanced in many standard works on hydraulics, to wit, that the erosion of the banks and bottom of streams like the Mississippi is due to the *friction* or *impingement* of the current against them, has served to embarrass the solution of the very phenomena presented in the formation of the delta of the Mississippi. In the bends, the centrifugal force of the water *makes the current more rapid on the concave bank of the stream*, and there it usually gets its additional load, and the caving in of the bend testifies to the rapacity of the water at that point of its course. Once loaded, however, it can carry no more, and hence it may sweep around half a score of other bends below with equal velocity without injury to them."

In justice to the eminent men who wrote the words thus quoted, it must be admitted that in many respects the opinions which they expressed were well founded and were sound, and that when these opinions were erroneous, such as that the maximum velocity of the flow in the curved bend of a river will be found along the outer bank (which both asserted), and that a current once loaded to its maximum transporting power at a concave bank might flow round "half a score" of concave banks below without causing any erosion therein, as Mr. Eads thought and said, the errors were due to lack of full acquaintance with the details of the manner in which waters flow along and around bends, which

[1] By E. L. Corthell, D.Sc. (p. 29).

lack they shared with the great majority of their compeers and their contemporaries.

The main channel of the Clyde abreast of Greenock presents an excellent example of a bight in a tidal river in which the flow of water round bends may be studied on a large scale, and it is interesting to note that in a series of special observations carried out in 1862, by Captain Calver, R.N., for the purpose of a report which he was instructed to make to the Lords of the Admiralty in respect of certain dredging operations which were then proposed in the interests of Glasgow, and to which the Greenock authorities offered a strenuous opposition (subsequently shown by Captain Calver's report to be well founded), that experienced hydrographer noticed a movement "of the filaments" of water which took him "completely by surprise," and which, although described in terms of a somewhat ambiguous sort, was almost beyond doubt, similar to the movement which was apparent in Prof. James Thomson's models and was shown by him on his diagrams.

Two practical conclusions may be derived from the consideration of the subject which forms the heading of this chapter: one, for the engineer, being that all concave bends in rivers should be effectually protected against erosion; the other, for the navigator, that in steaming against the current along and around a bend in a river the line of least resistance will be found in proximity to the outer and not to the inner bank.

CHAPTER V

THE MOUTH OF THE RIVER

If the course of the river be followed downward through the estuarial area to the river's mouth, which is the line upon which the combined volume of the upland and tidal waters is finally discharged into the sea, the student will be confronted by a new series of problems and perplexed by a new congeries of questions.

Two outstanding questions must be determined at the outset, before any works are contemplated or any improvements considered.

These questions are first, Is the river's mouth obstructed by a bar? and secondly, Are any sensible quantities of sand and silt conveyed from the sea by the tidal column into the estuary?

Before pursuing the investigation upon which the answer to the query as to the existence or non-existence of the bar will depend, the conditions and causes which lead to bar formation should be recalled and reviewed.

In the case of a non-tidal river the existence and maintenance of a bar is due principally to the conflict between the silt-bearing river, which under the power of the kinetic law referred to in the quotation from "The Story of our Planet" in the preceding chapter, seeks to dispose of its burden upon the sea bed as it loses its velocity in the wide and deep waters; and the sea which, as has already been shown, seeks to throw back through the agency of wave action, into the river or upon the foreshore the incubus which was originally derived from the land.

The Danube discharging into the Black Sea, and the Mississippi discharging into the Gulf of Mexico, furnish familiar examples of bar-encumbered rivers of this class.

In the case of a tidal river with its waters rising or falling in response to the movement of the tidal wave along a coast on

which the tidal range is considerable, and the drainage area comparatively small, the existence of the bar will be found to be almost wholly due to the marine wave action which tends, except where held in check by the discharge of land water reinforced by the scouring counteraction of the tidal ebb, to form an unbroken beach upon the margin of the sea.

The outlets of such rivers as the Tyne on the east, and the Mersey on the west of England, will serve as examples of this action and counteraction.

If a bar be found to exist at the mouth of a river which conveys the run-off from a great watershed to the sea and at which the tidal rise is inconsiderable, it may be concluded that the encumbrance is due to a combination of these causes.

Marine wave action is not only the occasion of the building up of a bar at the mouth of a river in such instances as those referred to, but in other cases operates in reducing depth by producing a flattening of the slopes of the channel of the river, thus increasing the area of the channel and correspondingly diminishing velocity and scouring power. The harbours of Pensacola and Galveston are both situated on the northern shore of the Gulf of Mexico, their circumstances and surroundings, their tidal range, etc., are much the same, yet under natural, *i.e.* unimproved conditions, the channel to Pensacola had a depth of 20 feet, while that leading to Galveston had a depth of 11 feet only, the difference being due in the main to the greater exposure and consequent increased effect of wave stroke at Galveston (Fig. 6).

Examination of the plans of the estuaries of the world will show that the form of estuary which is best adapted for resistance to the effort of the sea to block the entrance and thus to produce a bar at the mouth, is that in which the banks gradually diverge from the head to the seaward boundary in such manner that the tidal compartment widens gradually as the sea is approached. Estuaries of this form, even though obstructed in parts by sandbanks and deposits of silt, are generally free from the bar encumbrance.

The estuary of the Thames will serve to exemplify this statement, so will that of the Seine, and so, although the conditions are different, will that of the Severn, while another more distant but equally striking example is that of the river Tamar, which drains about 4610 square miles of the northern part of Tasmania, and discharges into Bass' Strait.

The observation of the phenomena at the mouth of an estuary is not business which should be entrusted either to amateurs or to novices, and comparatively little need be said about it here, but certain of the points to be considered may be noted.

First of all, the resultant direction in which the drift moves along the coast should be ascertained (if it moves at all) and an estimate made of the average rate of progress. By "resultant" is meant the ultimate result of the movement, as sometimes it may appear to be in one direction and at other times in another. Then

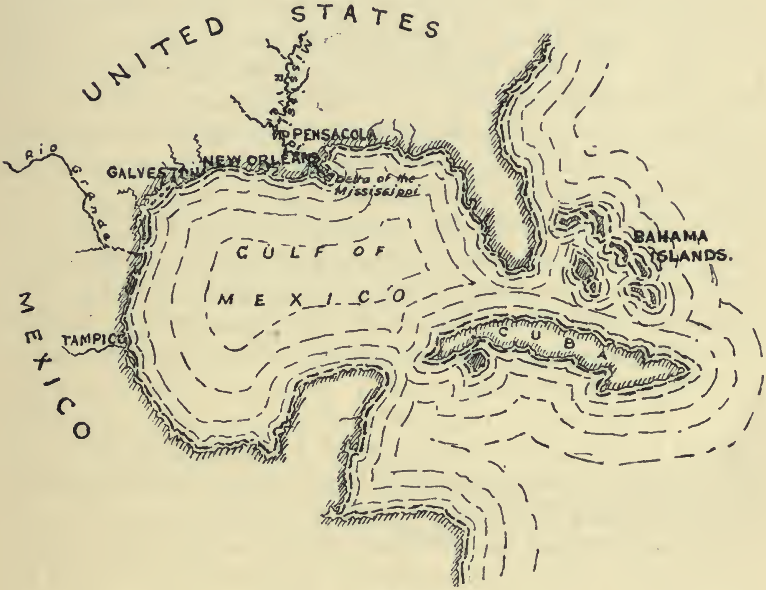


FIG. 6.

the causes which produce the movement should be traced and identified, however laborious the effort may be. The set of the tides and their strength at various periods should be laid down, and the direction and force of the prevailing winds noted; if there be any true littoral current its line should be laid down and its effect upon the tidal currents observed. The student should be warned that reflex action is not uncommon in the case of a littoral current, and that in consequence of this action the line of the current may not coincide with that of the prevailing winds; indeed the one may even be contrary to the other. The height of

the waves should also be measured, and particular attention should be paid to the effect of the wave stroke on the cliffs and beaches.

When no bar exists at the mouth of a river these difficult enquiries become of comparatively small importance, and little difficulty will ever be experienced even in the farthest parts of the earth in deciding whether a bar exists at the mouth of the river or not; but determination of the question as to whether silt and sand are carried by the flood tide into the estuary of the river is not so simple a matter. Appearances are very apt to be misleading in this respect, and a final conclusion cannot be safely reached unless and until actual tests of the quality of the inflowing water have been made. It is not necessary to incur the expense which would be involved in attempts to test large quantities of the water, a wooden box with an internal capacity of one cubic foot secured to a pole and fitted with a small door controlled by a spring, will furnish samples of bulk sufficient to supply the indication required. The samples should be taken at least thrice during the period of flood, beginning at about one hour after the turn of the tide, so as to permit of the inertia of the outflowing waters being overcome, and of the effect of the inflowing current upon the material in the bed being felt. The samples should also be taken at two points in the depth of the stream: one point within a few inches of the bottom, so as to ascertain whether sand is being rolled inwards by the stream, and another at about half depth, so that if material in suspension is being borne into the estuary, a sample of it may be trapped in the experimental box.

It is obvious that the answers to the two outstanding questions propounded at the beginning of this chapter will have a profound influence upon the design of works for the improvement of an estuary and of the river to which the estuary owes its existence; but the other matters to which attention has hereinbefore been directed must be considered in detail, as it is not until all possible information has been collected and collated that the student may safely begin the serious consideration of the problem before him; it being the first essential in such consideration that he should place himself in a position in which he can do his duty to those who are bearing the burden of the cost of the investigation, without doing discredit to himself.

The experience of the past has shown clearly and frequently that the lack of this patient and painstaking investigation of

conditions and observation of phenomena has led, in the construction of works, to results of the most disappointing kind, both to the engineers responsible for the works and to their employers; results which showed that instead of directing and regulating the forces of Nature, a position of antagonism to these forces was, in the design of the works, unwittingly taken up; so that efforts at improvement have been nugatory and expenditure futile; or even worse, the attempts to improve have made bad worse, and have hastened the destruction of channel and waterway which Nature was slowly accomplishing.

The jetties at the mouth of the Rhone may serve as a warning in the one case; the land reclamation works and the groynes in the estuary of the Dee below Chester in the other.

But human vision is limited, and human judgment is fallible; and even when the investigation of conditions has been undertaken and the observation of phenomena has been completed, errors may still be made, indeed not only have been made in the past, but have, in some cases, been proved to be beyond remedy. So that some method of experimental research by which conclusions may be checked and designs tested, has long been required in such a matter as the projection of works for the improvement of an estuary, or of the mouth of a river.

A method of research, such as that thus suggested, was introduced by a man of original genius in the latter part of the nineteenth century, was subjected to the criticism of a tribunal of high scientific and practical attainment, was approved by that tribunal, and will serve as the subject of a later chapter.

CHAPTER VI

RIVER IMPROVEMENT WORKS

River improvement works have generally an objective with a major and a minor motive behind it; the major being the provision of facilities for navigation, and for the furtherance of trade and commerce; and the minor the increase of the means for the discharge of superfluous rainfall so as to prevent disastrous floods.

It is a question whether in a densely populated country like Great Britain the order of motive should not be reversed, so that the much neglected feature of flood prevention might have the first place instead of the second; but in any case, the fact that operations for river improvement ought in the national interest to be carried out so as to ensure flood prevention as well as to provide direct commercial advantage, serves to condemn Brindley's maxim that "rivers are only useful to feed canals," and to require a reversion to the original method of river canalization as against the later system of canal construction on lines apart from rivers which Brindley and his successors advocated as the only way of escape from the difficulties attendant upon the working and maintenance of the canalized river, and which arose out of the fact that the river remained as the line of flood discharge, and consequently, as the line of transport of material from the higher levels to the lower.

The canalization methods of the eighteenth century, not only did not diminish the effects of floods, they increased the effects; as the practice was to obstruct the flood channels by ill-designed solid weirs, built at right angles to the course of the stream, and approached by long paved slopes. In the earlier part of the nineteenth century effort was made in such a case as that of the Severn navigation, to improve upon the old method by building weirs on diagonal lines across the watercourse in order to increase discharging power by lengthening the crest line of discharge; but

the deflection of the stream lines as they flowed to and from the weir with the consequent eddying and heaping up of level went far to neutralize any advantage which was gained by the lengthened weir crest; at any rate the method was ineffective, and is obsolete. Later on in the century, as the principles of hydraulic flow became better understood, the paved sloping approaches were abandoned, and weirs were built with vertical backs, and with crests formed in approximate accordance with the lines of the flow. This change was a distinct improvement, it was a step in the right direction.

One of the first and most important of the duties of an engineer engaged in the regulation, or as continental engineers would say the "normalization," of a river is to fix the areas of the cross sections of that river. In the discharge of this duty regard must always be had to the operation of the very obvious law that "when the sections of a river vary, the quantity of water remaining the same, the mean velocities are inversely as the areas of the sections." Obvious as this law is it is sometimes forgotten and its operation overlooked.

For the regulation of a river it is frequently necessary to construct weirs at suitable points, but the solid type of weir is out of date; it is now essential that the weir by which the river is to be controlled must itself be under control, and must be capable of removal in times of flood, wholly or in part, according to the volume of excess water to be discharged.

Many forms of removal weirs are in use, the majority being remarkable rather for eccentricity than for either simplicity or efficiency. The better known types are the "Needle" weirs, much affected by French engineers; the "Bear's trap," largely used in American waters; and the weir formed by a row of vertically-lifted sluices, which is in use on several British rivers, and which is the simplest, the safest, and the most easily manipulated of all.

The substitution of a single row of flood sluices for two solid weirs on the Weaver Navigation in Cheshire, furnished an interesting example of the way in which river improvement for navigation purposes may be combined with the abolition of destructive flood effect. Prior to the construction of the sluices the town of Northwich, which is situated on the river Weaver, and of which a considerable part is, owing to the subsidence caused by brine pumping, only 3 or 4 feet above the ordinary level of the river, was regularly inundated owing to flood rise in the stream,

even after the river channels had been deepened. The substitution of the sluices at Dutton for the Acton and Pickering weirs took place in 1881, since which time there has been no flooding in Northwich, even though the sluices are 8 miles below the town.

A similar effect though on a larger scale, has followed the construction of the Manchester Ship Canal. Flood damage has been eliminated from the city of Manchester, the borough of Salford, the borough of Warrington, and from many miles of the valleys of the Irwell and of the Mersey; even from parts where damage has been most severe, and from places where it had had results which can only be described as ghastly.

In the higher reaches of the river the damage still continues, but that is because the improvement has not been carried sufficiently far inland, so that the watercourses are tortuous and inefficient, and are still blocked by solid weirs, ill-designed bridges, and other similar obstructions.

The markedly successful and yet incomplete character of the flood-prevention work accomplished through the construction of the Ship Canal leads to another consideration. The indirect return on capital expended in river improvement for the prevention of floods is enormous, but the direct return is small and seldom accrues to the people who find the money for the improvement works. It cannot therefore be expected that private enterprise will provide the capital for such works, and it seems clear that the improvement of rivers as flood courses should neither be left to private companies nor to local corporations, but should be undertaken by Drainage Boards with statutory powers of control and regulation in the watersheds; authorized to acquire lands, remove obstructions, regulate stream courses, cut off bends, protect banks, and last but not least, effectively safeguard the streams in each watershed against pollution, whether caused by sanitary authorities or by manufacturers.

It has been whispered that in the pigeon-holes in the office of the President of the Local Government Board, there reposes the embryo of a Bill which may not go as far in the direction here suggested as engineering requirements and the needs of this country demand, but which if enacted would be a step on the way thereto; and that when the more exciting political questions of the day have burnt themselves out, an interesting event may be expected, and the birth of the Bill for the establishment of River Boards in Britain may be hoped to take place.

Great Britain is too small in area and too great in population to be able to afford needless loss through flood damage such as was experienced in the South and in the Midlands in the latter part of 1910 (to take one example only out of many), when great areas of autumn-sown wheat were destroyed, when the permanent way at Loughborough Station on the main line of the Midland Railway was knee-deep in water, and when difficulty was experienced in the supply of waggons at various ocean ports because goods stations at great inland cities were inundated for days together.

It is much to be regretted that a valuable opportunity for drawing public attention to questions relating to flood damage and flood prevention was lost, when the Royal Commission on Canals and Inland Navigations prepared and presented their Fourth and Final Report, issued in 1909. The Commission seem to have looked upon these vitally important matters as being beyond the scope of their inquiry, and referred to them in the most meagre of terms only; such references as they made being confined to bald statements as to interruptions to traffic on one or two navigations by the passage of floods.

In the Final Report on Canals and Inland Navigations in Ireland, issued in 1911, the Commission did take rather a bolder line with regard to "questions of drainage" and to "the use of rivers for the prevention of floods," and stated in an apologetic way that they had been "obliged to take notice" of these questions, as in certain rivers (they instanced the Barrow and the Bann) interests affected by drainage "are at present, of greater and more pressing importance than those of navigation."

If the Commission had felt "obliged to take notice" of like questions in England they would have been able, without difficulty, to compile a much longer list of rivers concerning which the same pronouncement might have been made.

The letting slip by the Commission of so great an opportunity was the more unfortunate, as had they availed themselves of it they might have saved their Report from the oblivion which now seems likely to overtake it. Schemes for waterways proposed for the purpose of competing with the railways and of reducing the rates thereon, would, as a matter of course, be regarded by the railway interests as an attack upon them, and railway companies are not corporations who, when they are smitten upon one cheek are disposed to turn the other; on the contrary, promoters of the schemes would find the whole of the great resources which

the railway companies control arrayed against them in one solid phalanx of ruthless and determined opposition. It does not require very keen vision on the part of the student of these questions to enable him to see what a point of vantage would be gained by the promoters if they could show that their schemes comprised improved facilities, not only for navigation, but for the passage of floods in times of storm and threatened disaster.

Works of the character suggested in this chapter would not put an end to the transport of material from the uplands to the estuary, but they would (1) check destruction and therefore diminish the quantities of transported material and (2) facilitate transport so as to lessen deposit in the channels of streams until the point is reached at which, in the interest of navigation, the sectional area must be so enlarged and velocity reduced to such an extent that practically all the suspended matter will be deposited and must therefore be removed by dredging.

Dredging silt and *detritus* (except in a heavy sea) is a simple operation and is not costly. Apart from the provision of the plant one penny per cubic yard should always cover the cost of dredging soft material; as the complexities arise, the difficulties are met, and from 80 to 90 per cent. of the costs of the removal of the deposits are incurred, in the transport and disposal of the material after it has been raised by the dredger.

For this reason if circumstances bring the acquisition of low-lying land at the head of the navigable part of the river within the limits of reasonable expenditure, a proposal for further expenditure for the widening and deepening of the channel to such an extent as to compel deposit at a place where it can be dredged and pumped ashore at a minimum of cost, and with an absence of obstruction to navigation, will be justified and may be recommended to Navigation Trusts and River Boards.

When a canalized river terminates in an estuarial channel the continual expenditure on dredging for the maintenance of the navigation can be viewed with some satisfaction, when it is remembered that the destruction of the estuary is being postponed through the interception and deposit elsewhere of the *detritus* which would in the natural course have found a resting place within the estuarial area.

Very little information is available upon which estimates of the quantities of material annually deposited in an estuary can be based, as even in cases where the material is intercepted and

dredged, and where the quantities dredged are measured with a fair degree of accuracy, circumstances almost invariably complicate each case and render the data uncertain.

In the case of the Manchester Ship Canal, practically the whole of the *detritus* derived from the watershed for which the canal is the "river," has for many years been intercepted in the waterway, dredged therefrom and deposited either on low-lying lands or at sea. The average quantities dredged annually have been found to represent a mean denudation of about 1·97 cubic yards per acre, or in other words, of about $\frac{1}{70}$th part of an inch in depth over the whole drainage area, the average rainfall in the area being about 38 inches.

The figures may be taken as furnishing some guidance for estimating the quantities of dredging which will be required for the maintenance of a river in a manufacturing district, which has been regulated and controlled for navigation purposes; but before they can be applied for the determination of the quantities of material, eroded from the land by natural operation and transported by the stream to the estuary; a factor, which will vary in varying districts, must be applied to them for the elimination of the proportion of polluting and encumbering material dredged from the waterway—and therefore included in the figure—the deposit of which was not due to the operation of Nature, but to the unlawful acts of men.

Where solid weirs are replaced by sluices, or where sluices are employed in the first instance, the sluice sills should be laid at or below the level of the bed of the reach which they are to control, the sluice area should be calculated on the assumption that the coefficient of contraction and of additional friction will, for sluices from 30 to 50 feet in width, be ·60, and the piers between the sluices should be made of the minimum width required for stability in times of heavy flood.

In determining the dimensions of flood sluices, which are of course permanent works, account must be taken of the fact, that as the population in any watershed grows and the proportions of the areas thereof in which paved streets and yards, slated roofs, and well drained properties, have been substituted for pervious surfaces and undrained lands increase, the rate of run-off increases also; which means that floods will become more and more concentrated, and therefore if not promptly discharged, will also become more and more destructive; or to put it in another way,

flood intensity will grow while flood duration will diminish. On the other hand when sufficient provision is made for the discharge of floods, growth of intensity should be welcomed in the interest of the conservation of rivers, as in the words of the old formula, "the force of water in deepening a channel is always proportional to the quantity acting in a given time."

Protection of banks and slopes from the destructive effects of erosion requires not only careful consideration in the first place, but constant attention subsequently. It is only by such protection against the undercutting action of floods that any sensible diminution in the quantities of solid matter brought down by the river can be secured. Where the river is to be rendered navigable by steamers, erosion due to the wave generated by the passage of vessels must also be taken into account in designing protective works. The effect of this wave action is nothing like so extensive as it is frequently supposed to be, as the eye always greatly exaggerates the range and extent of wave action. In a canalized river with a width of say 200 feet at water level no damage will be done by the wave action produced by a vessel steaming at the rate of 8 miles per hour if the slopes be protected for vertical distances of 3 feet below and 3 feet above water level respectively, but as it is almost impossible to restrict the smaller vessels (which cause the most damage) to that speed, prudence requires that the belt of pitching should extend from 4 feet below to 4 feet above water level.

Experiment and experience have alike demonstrated the sufficiency of these figures, and have shown that limestone rubble, hand-packed into place, and with an average thickness of fifteen inches is, where available, an economical and effective material for slope protection; while systems such as those now in use in Holland and on some of the rivers in this country (including the Thames) of protection by means of small concrete slabs have many advantages where limestone is not to be had at a reasonable cost. The hand-packed rubble method of protection has been adopted for the Kaiser Wilhelm Canal after exhaustive trials of many methods and systems, and has, as has been the case on the Manchester Ship Canal, been found to have special value where the whiter limestones are used, as the bank protection serves to pick out the lines of the banks for pilots when navigating vessels by night.

CHAPTER VII

ESTUARIAL WORKS

THE next group of questions to be considered are those which arise in connection with the improvement for navigation purposes of the channel through the estuary of the river.

It may be well to recall here principles already enunciated relating to the deposit and movement again of water-borne sediment; and also to suggest, as a cautionary note, that, in preparing designs for estuarial improvement works, prudence requires that the difference of standpoint between the interests which are established on the seaboard, and those which have their centres further inland, should be kept in view. The estuary is *inter alia* a natural provision by means of which the sea and its advantages may be borne in to the dwellers on the "foothills" (as the Americans call them), and those who think that the men on the coast, who regard the sea and the advantages thereof as their birthright, should look benevolently on proposals to improve the estuarial channels in such way as to enable the hillmen to share in what the coastmen consider to be their heritage, expect too much from human nature.

In most estuaries the channels are essentially unstable, in many they are diverse, the flood tide taking one course, and the ebb the other; while the upland waters, varying in volume from day to day, pursue lines of their own, reinforcing here, baffling there, and conducing generally to diversion and to change of course.

In such cases modern efforts at improvement begin with works for the regulation of the main channel in the estuary, and for the concentration therein of all the conflicting streams; the lines of flood and ebb should be trained in such manner that they will follow the same course, and into that course the lines of upland water should be directed. For these purposes longitudinal "training

walls" or "dykes" are now most frequently employed, groynes and spurs of varying kinds and sizes being made use of at the outset of the operations, first, because they can readily be extended or reduced in length and so permit of the line of the channel being finally determined by actual experience; and secondly, because the cost of the groynes is, at the outset, much less than that of training walls.

Training walls are in effect no more than the slope protection works already described, but are somewhat different in form, being generally deposited in place as a mound of rubble, or where stone is difficult to obtain and unduly costly, of stone mixed with clay. The lines of training walls should be carefully laid down, regard being had to the paramount fact that to be successful their function should be to regulate and not to thwart the efforts of Nature. The lines should diverge from the head of the estuary downwards, the degree of divergence depending largely upon the proportion between the volume of a land flood and the volume of tidal water which passes into the estuary upon an average tide. Where the upland water forms a considerable proportion of the combined discharge the divergence should be greater, where the proportion is inconsiderable, it should be less. In practice the variation in divergence has not been very great, except in the case of the river Seine, where the divergence as originally laid down, 1 in 200, was found to be too small. In the regulated channel of the river Weser, between Bremen and Bremerhaven, the divergence was 1 in 71; in the river Tyne and in the Nervion (from Bilbao to the mouth) 1 in 75; in the river Clyde (from Glasgow to Dumbarton) 1 in 83; in the river Vire and in the Maas (from Krimpen to Vlaardingen) 1 in 100; while in rivers in which the channels are more or less in natural condition, such as the Thames, the Humber, and the Scheldt, and in the Maas (below Vlaardingen) the divergence is nearly 1 in 50.

Each curve should be of as large radius as practicable, straight lines should be avoided even at the junction of two reverse curves. The work of deposit should begin at the head of the estuary, and the formation of the wall on the concave side should be undertaken first, as in many estuaries where the tidal range is small, it will be found that the concave wall or walls will fulfil the purpose required, and that the formation of walls on the convex parts of the channel may be dispensed with.

Dredging will, in most cases, be required at the outset; one

of the first objects of the dredging being the lowering of the inclined low water level. It is never possible to lower the low water level at the head of the estuary to that of low water at the seaward end, but much may be done to reduce the angle of inclination and to regulate the line of low water; and it is important to remember that the lowering of low water level has not only the invaluable effect of inducing larger quantities of tidal water to flow into and out of the estuary on each tide, and of thus compensating whether altogether or in part, for any reduction of capacity which may follow upon the construction of the training wall or walls; but it has the further effect of concentrating a greater part of the incoming and outgoing waters in the line of the trained channel, and of thereby increasing the potentiality of the flow as a scouring and transporting agency.

The questions relating to the problem as to whether reduction of tidal capacity can or cannot be safely undertaken in estuarial indents have been hotly debated by past generations of learned counsel and of engineers of repute and of experience; the heat imported into the discussions being, it must be admitted, due to the circumstance that in most cases the disputants were engaged as partisans and advocates for or against particular schemes proposed in one interest or another: a condition of affairs which did not lend itself to calmness of scientific contemplation, to unemotional judgment, or to the expression of impartial and unbiassed opinion.

No answers of a general sort can be suggested to these questions, each case must be considered by itself and with regard to the circumstances which are particular to itself, and to the environment from which it derives its peculiar temperament—its idiosyncrasy, so to speak.

It is however, well in the first place to consider whether any true reduction of tidal capacity will follow upon what may be admitted to be tidal displacement, as such displacement may be merely diversion of tidal flow from one position in an estuary into another position, a change out of which benefit may, and frequently does accrue; as in cases in which the filling up, or the closing, of arms and pools on the sides of a tideway have led in the past, and may lead in the future to an increase of the tidal height farther inland, and thus had the effect and may become the occasion of the replacing of almost useless waters by valuable flow.

The existence or non-existence of a bar at the mouth is an

important element in consideration of the questions; another point of great importance in the study having relation to the movement of sand and silt at and about the mouth of the estuary, and particularly as to whether such sand and silt are borne into the estuary from the sea or not.

The positions of the sites at which displacement of tidal water may be contemplated are also of moment; the distance from the mouth of the river, and therefore the length of the channel through which the displaced waters would flow, before being met and checked by the flood tide, should be taken into account, while a point which is frequently overlooked in these discussions is the improvement which may be effected in the scouring force of land floods by partially enclosing embayments, in which the great volumes of water derived from these floods spend their force and dissipate their efficiency as remedial agencies for the erosion and transportation seaward of previously deposited materials.

Broadly stated, the conclusion may be accepted that even in estuaries in which appreciable diminution of tidal flow may be caused by reduction of tidal capacity in certain positions, the diminution may be compensated for by increased concentration of flow and of consequent increase in the scouring power of the tidal column and in the energetic efficiency of the land floods.

The questions relating to the possibility, or otherwise, of improving the channels either in estuaries or in non-tidal streams by means of the concentration of flow, or by "the attraction of the waters," has not received as much attention in this country as in other lands, mainly because less scope for such operations can be found in the British Isles than abroad, owing to the comparatively small sizes of British rivers.

Professor V. E. de Timonoff of St. Petersburg, an eminent hydraulic engineer with large experience of great Russian rivers such as the Volga and the Dneiper, presented a useful report on this subject to the Eighth International Congress on Navigation, held in Paris in 1890. In that report Professor Timonoff described the system of "training by dredging and attraction of the waters," in which after the excavation of a channel suitable for the required navigation by means of specially powerful dredgers, and the determination of the most stable direction in the channel by positive experience, the channel is fixed by "plain and economical works." The deep thus provided and fixed offers a line of least resistance to flow, so that both velocity and volume of flow are

increased and waters are attracted towards the deep from neighbouring parts of the river. Professor Timonoff instanced the French river Garonne as exemplifying the results which may be achieved by this method of "attraction of waters," which he proposed should be applied to certain of the larger rivers in Russia.

Mr. Timonoff stated that in his study of the question he had been "inspired by the theoretical researches of French learned men and the experiments of American Engineers," in which connection allusion should be made in passing, to the excellent results which have been secured by American engineers by the application of the principle of concentration to the mouths of shoal-encumbered rivers, and to which more detailed reference will be made in a later chapter

CHAPTER VIII

SOME EUROPEAN EXAMPLES

The river Seine affords an example of training-wall construction, which was effective for the purpose for which the works were projected, but which led to an amount of silting behind the walls which was as unnecessary as it was unexpected; the case is therefore valuable (*a*) as an instance of systematic and useful work accomplished after years of effort; (*b*) as a warning against the employment of prophetic language as to the effect of operations in an estuary; (*c*) as a testimony to the necessity for prudence in the determination of the height of training walls; and (*d*) as a typical example of the differences of opinion which so frequently arise between the seaboard interests (represented on the Seine by the port of Havre) and those who dwell farther inland, who naturally desire to have direct communication with the sea, and who are in the present case represented by the manufacturing and commercial community at Rouen, also situated on the Seine, but at a distance of 78 miles from the sea.

Many schemes had been put forward for the improvement of the Seine, but none commanded public confidence until the proposal of M. Bouniceau, a Parisian engineer, appeared in 1845. M. Bouniceau's project consisted in the main in the construction of what he termed "longitudinal embankments," that is to say, training-walls on each side of the river, through which the low water channel could be regulated and fixed between Rouen and Havre. The project was received with favour both of a scientific and of a popular sort, was accepted by the Government of the day, and was begun in 1848, when training-wall construction was commenced at La Mailleray, some 37 miles below Rouen. In two years the work was carried forward to Quillebœuf, a distance of 18 miles from the starting-point, while in 1869 the two walls were carried down to Berville; after the experiment had been made

and failed, under which one wall only, that on the southerly side of the channel, had been formed. At Berville the work was stopped owing to an outcry from the Havre people, who thought that their prosperity was threatened, and who feared that accretion due to the construction of the walls would imperil the access to their port.

The lines of training were laid out in a workmanlike manner. The divergence between the two walls was at the rate of 1 in 200, or say 26 feet in a mile, which, as already hinted, proved to be too small and which hindered the tidal flow. The height of the walls on the contrary, was too great, particularly in the first instance ; as on the right bank down to Tancarville and on the left bank to La Roque, the walls were carried to a level equal to that of high water of an average tide, that is to say, of a tide halfway between high water of neaps and high water of springs. Below these points the heights were reduced, the level being that of the mean height of a neap tide, or half the height between the levels of low water and high water of a neap tide.

The effect of the works upon the condition of the channel between the embankments was altogether satisfactory. The level of low water spring tides was lowered to the extent of 2 ft. 3½ ins., that of low water neap tides was lowered 2 ft. 9½ ins. It was said that the height of high water was not affected, a statement which should be received with caution. The navigable depth in the channel to Rouen was increased to 18 feet, with the result that seaborne traffic developed to such an extent that Rouen, which had had an absolutely insignificant riverine traffic carried in small boats and barges, and no seaborne traffic at all, became the fifth port in France.

The works brought about a result of another kind, which gave colour to the fears of the people in Havre, and point to their somewhat clamant expression of those fears, and which had a prejudicial effect upon M. Bouniceau's reputation as a prophet; but which had as experience has shown no further prejudicial effect. M. Bouniceau had fully recognized that in the quiet waters in the spaces behind his high longitudinal embankments, silting would be inevitable, and thought that the accretion due to the deposit of material from the uplands would probably be increased by the transfer of material from the lower estuary, but concluded that the joint result would progress in so deliberate a manner that 21,000 years would elapse before any effect at the mouth of the

estuary would be perceived, and therefore considered that it was not necessary to attach practical importance to so remote a development.

As the construction of the longitudinal embankments proceeded it became apparent that there was something hopelessly wrong with the prophecy as to the 21,000 years. The protests of Havre became too much for the Government, so that the works were stopped, and a survey was made in 1875. This survey showed that the rate of accretion had been such that not in 21,000 years, but in less than a century from the time of the commencement of the operations, the silting up of the spaces behind the walls would be accomplished; the fact being that M. Bouniceau had in his estimate left out of account wave action in the sea at periods of heavy winds and storms when, under the combined movements of waves and tides, masses of terrigenous material are torn from the resting-place which they had found in the ocean bed, and are deposited in any space which they may find in embayment, indent, or estuary.

It is not possible to follow here the details of the more recent developments on the Seine, suffice it to say that eventually the training-walls were prolonged to the meridian of St. Sauveur on the north side, and to Honfleur on the south, with the result that the navigation to Rouen has been so greatly improved that steamers drawing from 21 feet to 25 feet (according to the tides) now reach that port regularly, while the depth in the outer estuary, so far from being impaired, has been improved; with the further result that the increase of the trade to and from Rouen may be measured by the fact that in the ten years ending 1902 no less a sum than £1,212,000 was spent in extending the capacity and in improving the facilities of the port; since which time the development has been continual, so that a scheme for the further extension of the training-walls in a seaward direction is now being considered by the French Government and by their engineers with a view to a further increase of the depth to Rouen (Fig. 7). It is interesting to note that while some of these experienced engineers are strong advocates of the extension of the training-walls, others look dubiously upon the proposal and would prefer the deepening of the channel by dredging only, relying upon the effect of the concentration which would follow upon the dredging for the maintenance of the channel.

But what about Havre? The Havre folk in the long contest

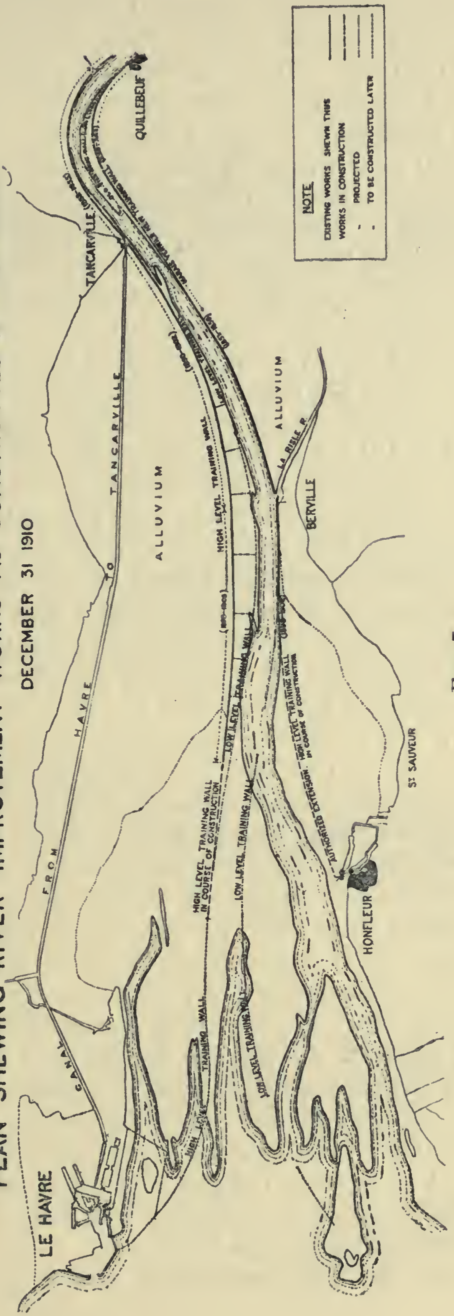

ESTUARY OF THE RIVER SEINE
PLAN SHEWING RIVER IMPROVEMENT WORKS AS CONSTRUCTED & PROPOSED
DECEMBER 31 1910
LE HAVRE
CANAL
FROM HAVRE TO TANCARVILLE
TANCARVILLE
QUILLEBEUF
ALLUVIUM
ALLUVIUM
HIGH LEVEL TRAINING WALL
HIGH LEVEL TRAINING WALL IN COURSE OF CONSTRUCTION
LOW LEVEL TRAINING WALL
LOW LEVEL TRAINING WALL
HIGH LEVEL TRAINING WALL
LOW LEVEL TRAINING WALL
HIGH LEVEL TRAINING WALL IN COURSE OF CONSTRUCTION
AUTHORIZED EXTENSION
LA RISLE R.
BERVILLE
ST SAUVEUR
HONFLEUR
NOTE
EXISTING WORKS SHEWN THUS
WORKS IN CONSTRUCTION
PROJECTED
TO BE CONSTRUCTED LATER

Fig. 7.

demonstrated their virility, and proved their powers as combatants; but events have shown that their fears were unfounded. It was admitted in the year 1880 that the accesses and entrances to Havre had suffered no injury. That was over thirty years ago. It should be noted that in the ten years already referred to a sum of £1,160,000 (nearly equal to that expended at Rouen during the same period) was spent in increasing and improving the dock accommodation in Havre, that in 1904 they had in Havre a depth of over 35 feet at high water of spring tides on the sills of dock entrances which are nearly 100 feet in width, and that the accesses to these entrances are from ½ metre to 1 metre deeper than they ever were before, so that most of the vessels afloat can be docked there at any time. Since 1904 Havre has again greatly extended its accommodation and increased its commerce (the traffic of the port in 1911 was 10,038,650 tons); and one moral to be drawn from the story of the Seine is that dwellers on the seaboard are apt to exaggerate the perils, both physical and commercial, which they think they discern in the distance when the inland people seek for themselves "a place in the sun," which in this case, means a way of direct communication with the ocean.

A further scheme is now being elaborated by the French Government engineers for continuing, though on a smaller scale, the improvement of the Seine from Rouen to Paris, a distance of 145 miles; the disastrous floods from which Paris and the surrounding districts suffered in 1910 and 1911, having given impetus to a project which for some time past has been slowly taking shape and form. The proposal is for an improved system of river canalization, after the manner of the Manchester Ship Canal, which will at once serve the commercial and shipping interests of the city and will provide an efficient outlet for land floods. Thus improvement leads to improvement, and development to development, and thus too, not merely are cities rescued from decay and provinces from declension, but great states and powerful nations are fortified and equipped for the struggle for existence, which in these times means more than anything else, a struggle for trade and commerce.

The river Clyde, around which so great an industrial population has gathered, is in some respects a parallel case to that of the Seine, while in others the Scottish waterway and the French present features of well-marked contrast.

The object was the same in each case, to place Rouen and

Glasgow respectively in direct communication with the sea for commercial purposes; and the means adopted were similar: in each river the channel was regulated and fixed by means of training-walls, the bed was deepened, the levels of low water were lowered, and thus flow was concentrated and velocity and volume were increased.

But there the resemblance ends. The Seine has a great watershed behind it, the catchwater area of the Clyde is comparatively small, so that while the natural scour of the combined land and tidal waters regulated and concentrated in the manner described, was sufficient for the deepening and maintenance of the channel in the Seine, the work on the Clyde has been almost entirely due to the dredging operations which have been carried on so effectively for so long a time.

Smeaton made his first survey of the river Clyde in 1755. He then found that spring tides at Glasgow only rose 1 foot 9 inches, while the rise at neaps was barely sensible.

Between that time and June 1910, over 80 millions of cubic yards of material of various sorts, ranging from hard rock to soft mud, have been removed from the channel between Newark Castle ($1\frac{1}{4}$ miles above Greenock) and Glasgow with the result that the low water line has been lowered over 10 feet, the rise of spring tides increased to 12 feet 2 inches, and large steamers enabled to lie and discharge and load cargo where Scotch boys once waded across the river.

In the case of the Clyde, as in that of almost every other river which has been improved by engineering operations, opinions differ as to whether any rise in the level of high water has been effected by the improvements. When dignitaries differ and authorities disagree it behoves students, who are a modest class, to hold their peace, to fall back on the operation of natural law (in this case the law of the conservation of energy) and to ask one another, not the dignitaries and the authorities in question, what can have become of the energy stored up in the tidal column which was at one time expended in overcoming resistances which are now non-existent? or how can that energy be expended under the changed conditions except in the raising of the level of that column against gravity, or in other words, in the raising of the level of high water at the inner end of the improved channel?

CHAPTER IX

SOME AMERICAN EXAMPLES

ANOTHER example (1) of bold engineering adventure, which like the Seine, has become classical (although the works were not the pioneers in their class), and (2) of marked effect produced by concentration of flow, is presented by the regulation of the South Pass of the Mississippi river, the "father of waters," which finds a place of discharge in the Gulf of Mexico.

The story of the deepening of the South Pass stands amongst the romances of public works as almost, if not altogether, the most romantic of them all. The completeness of the success achieved, the triumphant vindication of principle displayed, the indomitable resolution and courage required for the achievement, the persistence and resources of the powerful opposition arrayed against the scheme; all combine to render the narrative memorable in the annals of engineering; while the bright light of the ultimate triumph is brought out upon the screen by the darkness of a long history of failure in the background.

Efforts at improvement of the outlets of the great river date from 1726; of these efforts it is sufficient to say that they were varied in character, diversified in degree, and similar in effect. They all failed, and failed utterly, the fatal defect throughout being that no attempt was made to provide transporting power for material in suspension; and transporting power was just what was required in the diffused and obstructed passes through which the waters flowed into the Gulf.

The effort which furnishes such strong contrast to those which preceded it dates from 1874, when James B. Eads first publicly propounded his scheme for the rectification and deepening of the South-west Pass. The proposal furnished an admirable example of conditions under which successful engineering projects are conceived and designed, are advocated, and are executed; as it

was based upon accurate knowledge, of the sort which can be obtained by personal effort only, of hydraulic principles, and of the phenomena of the river in question; such knowledge as has in the foregoing chapters been insisted upon as essential before operations in rivers and estuaries can be undertaken with satisfaction and success.

In order that the character and extent of the operations may be understood, a few leading figures should be supplied here, through which the facts of the case may be grasped.

At "high water"—that is to say, when in flood—the Mississippi discharges into the Gulf of Mexico some 1¼ millions of cubic feet of water per second.

Like the Rhine, the Danube, and the Nile, the Mississippi discharges its waters through a self-formed delta. This delta is intersected by three main passes, which were supplemented by various gaps and crevasses, one of which (known as the Great Bayou) carried as much water as the smallest of the passes.

The main channels through the delta are known as the South-west Pass, the South Pass, and the East Pass; the latter, with the curious persistency of place-names, being more generally known by the old French cognomen, the *Passe à l'Outre.*

The disastrous effect of the diffusion may be measured by the fact that whereas at New Orleans, 107 miles from the mouth of the river, the stream with a width of half-a-mile had a depth of 150 feet; the respective depth in the passes were in the South-west 18 feet, the South 8 feet, and in the East (or *Passe à l'Outre*) 11 feet, the sectional areas in the same order being 60,000, 24,000, and 69,000 square feet respectively.

Eads' proposal was that the principles of diversion, concentration, and regulation of flow, should be applied to one of these passes so as to render it suitable for navigation by ocean-going steamers of large size; the concentration and regulation of flow being affected by means of parallel jetties at and about the shoal length in the pass, and the diversion by the construction of dams across certain of the gaps and crevasses through which so serious a loss of flow took place. For reasons which he advanced he selected and strongly advocated the South-west Pass for the great experiment, and so confident was he of the success of the operation which he proposed to carry out that he expressed his readiness to carry out the works at his own cost and that of his friends and supporters, on the principle of "no cure, no pay."

Surely no bolder offer was ever submitted to responsible authority in respect of a great engineering work.

The proposal was met with a storm of opposition on the one hand, and was supported by a large measure of public approval on the other, with the result that, as is so frequently the case, the promoters of the scheme were only partly successful; as although an Act of Congress was obtained in 1874, it provided for the improvement of the small South Pass, instead of the much more suitable South-west Pass.

The success, partial as it was, was largely due to Eads' own efforts; Eads who advocated the scheme in season, out of season; who to a great extent, wore down the opposition; who found friends and money for the work; and who carried it out in the face of almost overwhelming difficulties on his "no cure, no pay" principle, receiving no payment from the American Government until he secured first a permanent depth of 20 feet, then of 22 feet, then of 24 feet, and finally of 26 feet in the channel between the jetties.

The works were actually commenced in June 1875. The alignment of the jetties was worked out on an accurate survey of the South Pass which had just been finished; very complete data pertaining to the great river were in the possession of Eads and his colleagues; the unvarying and invariable principles of hydraulic engineering were closely adhered to; and the result was a triumph for the promoters, and a distinct gain, not only for the population interested in the Mississippi valley, but for the part of the human race which wear cotton clothing of one sort or another; for by August 1876, a depth of 20 feet had been secured; by February 1878, a depth of 22 feet; by July of the same year 24 feet, and by October of that year 30 feet.

The improvement has been permanent and complete, the depth has not only been maintained but has been increased, and so far from experience having proved that constant prolongation of the jetties has been required (as was predicted by opponents) Mr. E. L. Corthell, who was the resident engineer on the work, found in 1904 that the end of the eastern or windward jetty was actually 200 feet to the landward of the point where he laid it in 1875, twenty-nine years before.

No more cogent proof can be advanced of the entire success of the jetties than the fact that works on similar lines to those at the South Pass are now in progress at the larger South-west Pass,

where Mr. Eads himself desired to make his experiment, but was overruled by Congress.

The success of the works of the South Pass emboldened other authorities to undertake operations of like character for the improvement of the mouths of other rivers which flow into the Gulf of Mexico. Tampico is a case in point. Tampico is on the river Panuco, which discharges into the Gulf on the east coast of Mexico, some 300 miles to the southward of the Rio Grande, the boundary between the United States and Mexico (Fig. 6). The work of jetty construction was begun by Mr. Corthell at the mouth of the river Panuco in 1890, and completed in 1892. The results were again most gratifying. The river differed greatly from the Mississippi in size, the total discharge being about 15,000 cubic feet per second at high flood, and in character, as the discharge was effected through a single mouth instead of being spread over a fan-shaped system of channels. The ruling depth in the entrance channel was but little over 8 feet in May 1890, it had increased to 19 feet 6 inches in October 1892, and to 24 feet in January 1895, while the effect upon the trade of Tampico was correspondingly great, as from an obscure and unimportant creek the port grew until its traffic returns ranked second amongst those of Mexican harbours.

Mr. Eads' method of working has been followed in each case. Subsidiary streams and crevasses have been stopped and thus concentration of flow has been secured; the flow has been regulated by means of parallel jetties, while hard knots and obstacles in the channel have been removed by dredging so that resistance to flow has been reduced. By these means increases in velocity and in volume have been secured; in velocity, through which further power for erosion was brought to bear upon the bed of the Pass; and in volume, by which the additional transporting power required to bear the eroded material out into the Gulf was supplied.

The methods are simple, direct, and efficacious, and were in the first instance derived from the application of hydraulic principles and from the example presented by the works carried out by Sir Charles Hartley at the Sulina mouth of the Danube with such great success.

CHAPTER X

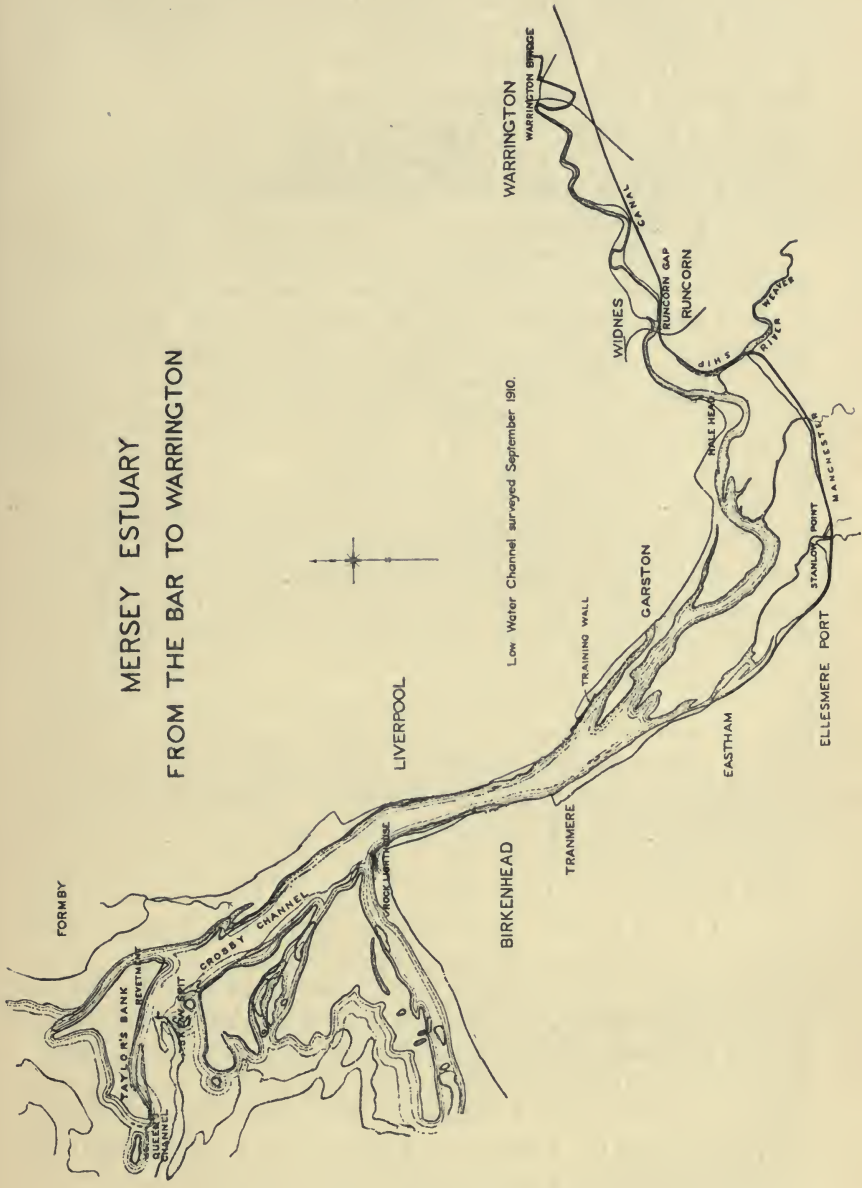
THE MERSEY

THE estuarial length of the Mersey was once described by the late Mr. Thomas Hawksley as a "raging wild beast"—a terse and rememberable expression, by which Mr. Hawksley, who was not given to paying unmerited compliments either to men or to things, meant that he regarded the Mersey as a difficult river to deal with.

All estuaries are difficult to deal with if public benefit is to be secured, but there is no gainsaying the proposition that in the Mersey the difficulties are acute and are always present, being due in fact to a combination of peculiar conditions at the entrance to and in the form of the estuary, as well as in the economic and commercial interests which have developed not only upon the banks of the river but in the *hinterland.*

The entrance is situated in one of the most stormy corners of the Irish Sea; it is in an embayment in which the tidal currents which have swept into that sea, northward through St. George's Channel and southward through the North Channel, meet and turbulently argue in their own way, questions of priority and precedence: one resultant condition of a secondary sort, being the great tidal range which is experienced in the Mersey during spring tides and from the effects of which Mr. Hawksley's epithet "raging" was derived. At high spring tides the range from low water to high water is 31 feet, while at neap tides the range falls to 10 feet, the tidal capacity of the inner estuary between the respective planes of low and high water, being at springs, about 710 million cubic yards, and at neaps about 280 million cubic yards.

The form of the estuary is singular, and may for convenience sake be divided into three portions, (*a*) the outer estuary, (*c*) the inner estuary and (*b*) the neck or conduit by which (*a*) and (*c*) are linked together. (Fig. 8.)


MERSEY ESTUARY
FROM THE BAR TO WARRINGTON
Low Water Channel surveyed September 1910.
FORMBY
TAYLOR'S BANK
REVETMENT
QUEEN'S CHANNEL
CROSBY CHANNEL
LIVERPOOL
BIRKENHEAD
TRANMERE
TRAINING WALL
GARSTON
EASTHAM
ELLESMERE PORT
STANLOW POINT
MANCHESTER
SHIP
RIVER
WEAVER
HALE HEAD
WIDNES
RUNCORN GAP
RUNCORN
CANAL
WARRINGTON
WARRINGTON BRIDGE

The outer estuary does not lend itself to lucid description. It is almost triangular in shape, the boundaries of the triangle being the coast lines of Lancashire and Cheshire (which at the junction of (*a*) and (*b*) form a re-entrant angle of approximately 90°) and the outer edge of an irregular mass of sandbanks which are partly exposed at low water of spring tides, which cover nearly 25,000 acres, and which have had their origin in the destruction of the marginal cliffs and banks of the upper estuary as well as of the coasts of North Wales.

Through these sandbanks a natural and fairly stable main channel serves for the inflow of the tidal waters and for the reflow of those waters combined with the run-off from the watershed. The seaward (and shorter) portion of the main channel is known as the Queen's Channel, the inward portion is termed Crosby Channel. There are subsidiary channels which need not be referred to in detail, they lead to diffusion of flow and of scour, that is, to the very opposite of concentration.

The outer end of the Queen's Channel was formerly encumbered by a bar which limited the capacity of the port of Liverpool and of all the other ports of the Mersey, and which lay as a sullen obstacle across the channel at a distance of some 11 miles below the Rock Lighthouse, which marks the line of the Cheshire coast and the junction between (*a*) and (*b*). This bar has been removed entirely by the heroic dredging operations to which further reference will be made.

The neck or conduit by which this outer estuary is connected with the inner estuary is about 6 miles in length and has some semblance in form to that of the *vena contracta*, the high water width at New Brighton (at the seaward end) being 1,760 yards, which diminishes to 1,000 yards at Seacombe, and expands again to 1,530 yards at Tranmere, where at present the "neck of the bottle" terminates and the upper estuary begins.

The upper estuary of the Mersey looked at on plan, has a curious similarity in shape to a side view of the skins of the water carriers which are yet familiar objects in some parts of the East. From Tranmere the banks begin to diverge and the width of the estuary to increase until at Ellesmere Port (about 12½ miles above the Rock Light) the width is over three miles ; from thence the width diminishes in a somewhat irregular way until at Runcorn Gap (18 miles from the Light) the natural width was under a quarter of a mile, above the Gap a second expansion occurs to a

width of 1,230 yards, after which the waterway presents the features of an ordinary tidal river of small and diminishing size, the width near Warrington Bridge (28 miles from Rock Light) being only 50 yards.

As a consequence of this combination of peculiar conditions, the Mersey furnishes for the consideration of the student, an almost unique example of the effect of the conversion of tidal momentum into current velocity in the neck or conduit, and again of the operation of momentum in the heaping up against gravity of the waters in a tidal stream in the upper part of the estuary.

At spring tides the velocity of the flow through the contracted vein, attains the remarkable limit of 7 miles per hour, while a tide "uninfluenced by the wind" which rises to a height of 21 feet above the level of Old Dock Sill [1] at Liverpool will rise to a height of 25 feet above the same datum at Warrington Bridge.

The contrast between the conditions which obtain in the main channel in the lower estuary, and those in the main channel in the upper estuary, will also be rife with instruction as well as with interest to students. For the greater part of its length the channel in the outer estuary is stable in course and direction, and where movement has taken place, *i.e.* where Crosby Channel bends towards the line of Queen's Channel, the movement has been due entirely to the sharpness of the bend, in which erosion has occurred on the concave side, and accretion on the convex, thus tending to make the sharp curve still sharper, precisely as in the case of a bend in the course of an upland stream flowing through an alluvial plain. For many miles in the upper estuary, below the length at which the Mersey becomes little more than a tidal creek, the main channel has during the last century meandered about the bed of the estuary to such a degree that there is no part of that bed in which the channel has not at one time or another found a temporary resting place; the mutations having been at some times slow, steady, and ruthlessly continuous; at other times sudden and violent, and affected by causes which appeared to be altogether incommensurate with the results which followed them.

Some of the recollections of an experience now extending over

[1] The "level of Old Dock Sill" is the datum to which all tidal heights are referred on the Mersey. It represents a level of 4·66 feet below Ordnance Datum, and is an unhappy relic of a dead past.

forty years may be recorded as illustrative of the mutations of these unstable channels.

What was once known as "the great fret of 1873," began by a very ordinary movement of the channel at Hale Head from the Lancashire side towards the Cheshire side of the estuary. No attention was paid to this, the channel was always moving; "fretting," *i.e.* undercutting of the banks of silt and sand on the concave sides of the bends, was normal in the Mersey; the way of the river being to swing the upper channel over to one side for a while and then reversing the process, to swing it back to the other. But on this occasion the progress from north to south was continued for years, until the channel fretted for itself a course into the bight which then lay to the eastward of Stanlow Point and the river Gowy, where, being stopped by a rocky reef, it swung back into the estuary, then fretted a way into the next embayment, that at Ellesmere Port (the Mersey terminus of the Shropshire Union Canal), where it wrecked the whole frontage of the port, cut the foundations from the feet of the walls, and left the walls nearly flat on their backs. This was in 1873–4, after which the channel, apparently satisfied with the results of its excursion to the Cheshire side of the estuary, reverted to the Lancashire shore, and remained there more or less for several years.

This "great fret" originated in and was maintained by natural causes, but estuarial changes of considerable extent, and followed by consequences of serious import, are sometimes caused by accidents of small degree, as to which little concern is felt in the first instance.

In the year 1874 a little coasting schooner went ashore on a sandbank in the Mersey between Hale Head and Runcorn Bridge, and there disappeared from sight, swallowed up by the sands as a rabbit by a boa-constrictor. In the process of deglutition that small and insignificant derelict caused so great a change in the upper Mersey, that the port of Runcorn was for the time being almost entirely blocked owing to the diversion of the deep from the entrances to the Bridgewater Docks.

Again, the fact that even changes due to natural events in estuaries are sometimes violent and very sudden, is instanced by the occurrence of such a change in the Mersey in the year 1880, when on one stormy summer's day (it was in the month of June) of strong gales and floods, the low water channel at Hale Head

changed its position laterally for more than a mile in less than twenty-four hours.

Finally, as small causes sometimes lead to great estuarial changes, so at other times apparently inconsiderable causes stop the progress of dangerous channel movements. About the year 1900 it began to be noticed that the low water channel in the upper estuary had begun a migration from north to south, which led to misgivings on the part of the few survivors who remembered the "great fret" and the havoc which it wrought at Ellesmere Port. The migration was directed towards Ince Bay, across which one of the embankments which separates the Manchester Ship Canal from the estuary had been formed; a circumstance which added point to the misgivings, and which led to a close watch being kept upon the movement of the channel. The movement proceeded steadily until 1906, when the works which had been undertaken preparatory to the raising of the water level in the canal had been completed, and a small brook which drains the Frodsham marshes and which had up to that time been permitted to flow into the waterway, was syphoned under the canal into the estuary. The waters of the brook cut a way for themselves through the expanse of mud-banks until they joined the low water of the channel, the dangerous movement of which they first checked, then arrested, and finally turned northward again until the channel resumed a position on the Lancashire side of the estuary, and the situation was saved for the time being.

The comparative stability of the channel in the lower estuary, emphasized as it is by the mobility of the deep in the upper estuary, is due, *first,* to the increased inertia derived from the increased volume of flow in the lower channel; *secondly*, to the more direct course of that channel and to the greater concentration therein ; and *thirdly*, to the much smaller proportion which upland waters and land floods bear to the tidal flow in the lower channel through which the disturbing influences of storms and floods are materially reduced therein.

Disturbing influences are not absent in the main channel in the lower estuary. The situation is an exposed one, and wind and wave affect the line of the deep, as witnesses the sharp bend in Crosby Channel, a difficulty which has called for remedial measures during late years, but a difficulty which is small, almost insignificant compared with that which was once presented by the bar, that formidable and permanent obstruction to the main

channel of the lower estuary, and to the traffic of the Mersey.

From time to time in the past, many schemes were propounded for the improvement of the access to the port of Liverpool, but up to the year 1890 practically nothing was attempted, although the increasing size of the steamers engaged in the North Atlantic trade rendered the obstructed condition of the channel more and more serious. At that time the depth on the bar varied from 10 feet at low water of springs, and 19 feet at low water of neaps; to 30 feet at high water of neaps, and 41 feet at high water of springs; which depths were about as good as those which were then available in the harbours on the east coast of North America, and were sufficient to enable practically all of the steamers then working the trade to leave and to enter at high water. But complaints were constant as to delays to large passenger steamers which had to lie outside the bar, sometimes for hours, waiting for the tide; not only that, but shipowners clamoured for vessels of larger size, and shipbuilders shewed themselves to be eagerly ready to respond to their requirements, so that the authorities which controlled the ports in which the American trade was handled were obliged to accept the responsibility of providing facilities for the leviathans which began to come into sight, and therefore to carry out operations for the improvement of their harbours and of the accesses thereto.

In the port of Liverpool the problems connected with bar improvement works were so complex, the expenditure which would be entailed seemed likely to be so great, and the results seemed likely to be so uncertain, that the responsible authorities were reluctant to attempt to carry out any works; and while desirous of meeting the requirements of the trade, felt compelled to maintain the position which they had occupied so long with regard to improvement works.

The alternative lay in an attempt to provide and to maintain the increased depth by means of dredging, and the result has been a series of dredging operations so bold, so impressive, and so successful, that no study of Rivers and Estuaries which left them without notice could be considered as complete.

The material of which the Mersey bar was formed, was mainly derived from the sea and was principally composed of sand; in this differing from the bars at the mouths of the Mississippi and other like rivers, which were composed of sludge

and fine silt brought down from the uplands; it was therefore suitable for suction dredging, which in suitable material has great advantages over bucket dredging. Mr. A. G. Lyster, the present engineer-in-chief to the Mersey Docks and Harbour Board, who (under the late Mr. G. F. Lyster) organized the plant and conducted the operations from the first, began in an experimental way, by fitting two steam hoppers with sand-pumps and suction-pipes. The hoppers had a carrying capacity of 500 tons each, and the experiment proved so successful that dredger after dredger was built until the series culminated in a suction-dredger of which the hopper capacity is 10,000 tons and the pumping plant is competent to lift and load this quantity in 55 minutes.

From the first modest essay to the close of 1910 this plant dredged the amazing quantity of 161,000,000 cubic yards—45,000,000 cubic yards from the bar, 56,000,000 cubic yards from Queen's Channel, and 60,000,000 cubic yards from Crosby Channel—the result being that a channel has been made and maintained through the bar and its approaches with a depth of from 27 to 32 feet at low water of spring tides (instead of 10 feet as formerly) and of 61 feet at high water of the same tides.

But improvement leads to improvement, the observation has already been offered in this study, and is repeated here because experience in the Mersey as well as experience elsewhere has shewn how well-founded the assertion is.

Reference has already been made to the sharp bend in the main channel of the lower estuary. That channel takes a course to the northward for about five miles, and then turns abruptly to the north-westward through sandbanks which are known locally as Taylor's Bank and Askew Spit; Taylor's Bank being on the outward or concave side of the bend and Askew Spit on the inner or convex side. The low water channel undoubtedly owes this peculiarity of form to the strong wind and wave action to which it is subject, and it is obvious that on the principles laid down by Professor James Thomson, the concavity in Taylor's Bank would increase and the convexity in Askew Spit would grow, so that in the course of nature the sharp bend would slowly but surely become sharper. The dredging of a straight and deep channel through the bar and approaches accelerated the natural rate of erosion on the concave side of the bend, owing in part to the increase in volume of the flow, but owing in even greater measure to the increased concentration which followed upon the improvement of

the channel: and the acceleration became so serious that it looked as if (1) the bend would become a peril to navigation and (2) the river would form for itself a subsidiary channel to the sea, and so destroy the position of advantage which has been won through the dredging operations which had been undertaken and had been pursued for so many years.

A case for the adoption of remedial measures had therefore been made out, and Mr. A. G. Lyster (now Vice-President of the Institution of Civil Engineers) recommended that the concavity in Taylor's Bank should be protected with limestone rubble for a length of about 2½ miles, in such manner as to put a stop to the erosion there.

After very careful consideration the Mersey Docks and Harbour Board accepted the recommendation and authorized the formation of the "training-wall" or "revetment," as the proposed work was termed. Both terms were accurate, as both implied that the slope of the concavity, which was formed of material which the currents as they impinged upon the bank were capable of removing, was to be protected by material which these currents were incompetent to dislodge or to affect.

The work so authorized was duly carried out, the limestone rubble being conveyed to the site in hopper barges, dumped upon the line of the upper part of the revetment, and left to adjust itself under the action of the tides to the slope of the bank. The success which was achieved was such that similar operations have been undertaken recently for the regulation of the tidal streams at and about Dingle Point between the southerly termination of the Herculaneum Docks and Garston.

This fact does not stand alone. The revetment in the bight of Taylor's Bank was only completed in 1911, yet already formal and official notice has been given of the intention of the Mersey Docks and Harbour Board to extend that revetment, and to construct training-walls on both sides of the channel of the lower estuary, between Taylor's Bank and the Rock Light.

It is only necessary to state the lengths of the proposed works in order to enable the student to grasp the extreme importance of the proposal and the serious nature of the experiment.

On the easterly or left-hand bank of the channel the length of the training-wall will be over 2½ miles, while on the westerly or right-hand bank the length will be over 5 miles, while the extension of the revetment at Taylor's Bank will have a length

of $\frac{3}{4}$ of a mile; so that it is now proposed to extend an existing length of $2\frac{1}{2}$ miles of regulative works to a total length of about 11 miles. Without venturing to assume the mantle of the prophet (a course which has already been deprecated in this study), it is but reasonable to suggest that finality will not be reached even if and when the works now proposed are carried into execution, as further lengths amounting in all to some 12 or 13 miles will remain untrained and unprotected, which the force of circumstances will almost beyond doubt, compel the Mersey Authorities to deal with, whether by way of dock extension or of training wall construction.

These protective and regulative works in the Mersey are of more than ordinary interest to students. The revetment at Taylor's Bank is probably the first work, to the design of which the principles enunciated by Prof. James Thomson were applied in actual engineering practice; moreover, for the purposes of the design Mr. Lyster and Lieut. Mace, R.N.R. (the Marine Surveyor to the Dock Board) carried out a series of float observations, by means of which not only were the lines and velocities of the currents in the bend of Crosby Channel determined both for flood and ebb tides, but the results obtained by Prof. Thomson in his model experiments and represented by him in his diagrams were verified and established by actual observations on a great scale.

The works have a further interest, as showing how the conditions of modern life, increasing as they are in complexity and in national interdependence as the population of the earth multiplies and develops, and as the trade of the globe grows and expands, impel and compel even the most cautious and conservative of authorities to take measures, to sanction projects, and to carry out operations, which neither their predecessors nor themselves would have been willing to consider a comparatively few years ago.

CHAPTER XI

ESTUARIAL MODELS

In the year 1885, when the Bill to authorize the construction of the Manchester Ship Canal was before Parliament for the third year in succession, and when engineering opinion was sharply divided as to the results which might be expected to follow upon the construction of the works proposed to be carried out in the valley and estuary of the Mersey, Prof. Osborne Reynolds, F.R.S., suggested a method by which he thought that the results likely to be produced by such works in rivers and estuaries could be indicated with a fair degree of accuracy.

Dr. Reynolds's view was that a systematic study of the conditions of a river falls naturally into three divisions:

(1) Observations of the general phenomena relating to the *régime* of the deep, *i.e.* the low water channel.

(2) The movement of sand corresponding therewith.

(3) The action of the water which produces these movements.

He therefore constructed two models of the estuary of the Mersey from the bar to Runcorn Gap, a distance of 35 miles. The first model had a horizontal scale of $\frac{1}{38000}$ and a vertical scale of $\frac{1}{960}$, with a tidal period of about 40 seconds, or 90 tides per hour. The respective scales of the second model were $\frac{1}{10560}$ and $\frac{1}{396}$, the tidal period being 80 seconds. Tidal flow and ebb were simulated in each model by the addition of a hinged tray at the seaward end, which was filled with water up to the level of low water, and raised and lowered mechanically.

The tidal period on which the velocity of flow depended was in each case based on the theory of the propagation of waves. Velocities vary as the square roots of heights; velocities in a model ought therefore to be to velocities in the river in the proportions of the vertical scales, and the times should be in proportion to the horizontal scales divided by the proportion of the velocities.

When the water was put into motion important changes took place in the distribution of the fine sand which was spread over the bed of each model; the reasons for the changes could be plainly seen, and after about 2000 tides in the small model and 6000 tides in the larger, banks and channels were clearly defined, and, particularly in the large model, presented despite the distortion, as nearly as possible a reproduction of actual conditions in the part of the estuary which had been modelled.

Professor Osborne Reynolds exhibited his models and described the results which he had achieved at the third International Congress on Inland Navigation held in Frankfort in 1888, and again at the fourth Congress held in Manchester in 1889. At the latter Congress the description excited much interest amongst continental engineers, and Mr. Mengin, then engineer-in-chief to the works in progress for the improvement of the estuary of the Seine, was so impressed by the importance of this experimental method, that he induced the Commission of Engineers, under whose auspices the Seine works were being carried out, to recommend the French Government to suspend further progress with the training-walls until the effects of these walls as then proposed had been tested on a properly constructed model.

Subsequently the attention of the British Association for the Advancement of Science was drawn to the possibilities which lay in so simple and practical a method of investigating a subject so complicated and difficult, and the Association appointed a strong committee to act with Dr. Reynolds in the matter, and made an annual grant for three years in succession in order to assist him in the conduct of his experiments.

Reports drawn by Reynolds and endorsed by his committee were presented to the Association in 1889–90–91. Somewhat regrettably the committee avoided the "very difficult task of modelling any existing estuary" and constructed instead a model of an ideal estuary with which they experimented.

(A) In a "natural" condition.

(B) With regulating works of various sorts.

(C) With tidal waters supplemented by upland waters flowing in at the head of the estuary.

As might be expected, the experiments demonstrated the marked effect which the discharge of the land waters had upon the channel in the upper part of the estuary.

Professor Osborne Reynolds summed up the results of the

experience in one sentence of his own, for he said that "the models showed that in any trained channel the depth could be maintained by scour, if that scour were supplemented by dredging," and the committee finally reported that

(1) The model system had been tested over a great portion of the ground which it is likely to cover.
(2) The difficulties which were likely to occur had been met.
(3) The precautions which were required to overcome these difficulties had been discovered.
(4) The system may, if these precautions are carefully observed, be applied with confidence to the solution of practical problems.

The conclusions of the committee were, as is the way with committees, expressed in terms of the most cautious and conservative sort, to which no exception can be taken, but for which allowance should be made; so that the conclusion of the whole matter may be said to be when (1) the course of observation of conditions and the study of data already recommended, have been perfected, and (2) works have been designed and a project for improvement has been completed, the course and the study should be supplemented by the construction of a model of the estuary in question, through which the effect of the proposed works may be tested experimentally, it always being remembered that to the indications supplied by the model the observer must add for himself the effect of wind action and of wave stroke.

The modelling of an estuary on a sufficient scale and with reasonable accuracy, for the purposes of experimental research and of the testing of the effects of proposed works, is a troublesome business which takes time and involves expense. For this reason, perhaps, it has never become popular, and is in danger of being allowed by the present generation to drop out of sight and memory. Unless this danger can be averted, a method whereby works proposed in an estuary may be proved by trial to be right or wrong will go through the process of *euthanasia*, and will sink into a place amongst the graves of the forgotten.

If this happens, a useful adjunct to the equipment of the student will be lost; a valuable aid to the arguments by which the engineer (whose duty it must become in increasing measure to recommend works for estuarial improvements) can support the advice which he has given will be discarded, and a means of

demonstrating the value of the works recommended to boards and authorities, which are composed of men who desire to do their duty but who are hampered by tradition, and burdened by fears of failure—having some knowledge of mistakes in the past—will be recklesly thrown away.

Having regard at one and the same time to the formidable difficulties which beset all questions relating to estuarial works and to the irresistible forces which are compelling public authorities to consider and to undertake such works, this note of warning against the abandonment of an admittedly useful aid to the investigation of the subject is sounded; while, for the purpose of deepening the note and in the hope of rendering the sound more effective, an old-time narrative of destruction and of disaster upon a great scale, which followed upon incompetent efforts for the improvement of a sea channel, is added; as it may be that in this way the warning will be emphasized by a picturesque illustration, and so this elementary study may be brought to a practical conclusion.

The story is that of the Gulf of Ephesus; which 3,000 years ago was a well-marked indent on the western coast of the peninsula which forms a bridge between Europe and Asia, which British map-makers call Asia Minor, but which was then known, in the speech of the Greeks, as Anatolia, the "place of the sun-rising." That western coast looked out upon the Ægean, which separated it from Greece, and the indent (which had deep waters and an area of about fifteen square miles) was sheltered from all winds except those from the west. At the head of the Gulf where the waters washed the feet of the mountains of Anatolia, emigrant Greeks laid the foundations of the city of Ephesus, which in process of time became a leading emporium, first of the traffic between the two sides of the Ægean and of the intervening Archipelago, and subsequently of the immense trade which was exchanged between the East and the West in the ancient world. On account of the position which it occupied, and because of the maritime advantages which it possessed, Ephesus grew to be one of the most populous, wealthy, and important centres of that great prototype of modern trade.

To-day the site of the Gulf of Ephesus has been silted up until it has become land, partly fertile and useful land, but partly land in the form of useless and unwholesome marshes through which the river Kayster pursues a tortuous way to the sea, while

F

the name of the great city Ephesus has disappeared from the map.

Strabo the geographer, himself a native of Anatolia, took an intelligent interest in the Gulf and in the history of its fortunes and misfortunes and has left the record for us. It appears that the history began about 1000 B.C., that the coastline, after seven centuries of disintegration on the hills and of transportation to the Gulf, had advanced seaward for about a mile, and that it proceeded to advance until somewhere about 150 B.C., when a King of Pergamum, Attalus Philadelphus by name, recognizing that the matter had become serious for Ephesus, called in an eminent engineer of the day, who carried out works in, and built a breakwater across the mouth of the Gulf, with the result that the channel through the Gulf was irreparably injured.

At the death of King Attalus, under the terms of his will, Anatolia became part of the Roman Empire and so came under the capable government of the proconsuls. Various governors made efforts at great cost, to maintain the access to Ephesus (a canal is said to have been formed across the growing deposits in the embayment), but these efforts were hopeless from the beginning and were relaxed as the Imperial power was weakened, and so the Gulf silted and so Ephesus sank into decay and death, until the name of the city alone is left "to point a moral" if not "to adorn a tale."

The "ill-advised engineering scheme" (as Sir William M. Ramsay has called it), which was intended to frustrate Nature's obviously destructive operations in the Gulf of Ephesus, can be seen, at this great distance of time, to have accentuated and hastened the course of destruction to no small extent; the name of the engineer who devised the scheme and carried out the works has sunk into a merciful oblivion, no doubt he did his best (as students are apt to say when they have tried and failed), but the best that can be said about him is that considering the state of knowledge in his day there was an excuse for him, which cannot be held to be valid in the case of any successor of his in this twentieth century A.D.

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THE END

PRINTED BY WILLIAM CLOWES AND SONS, LIMITED, LONDON AND BECCLES.